FUTURE TECHNOLOGY IMPROVEMENTS

Potential to improve Load Factor of offshore wind farms in the UK to 2035

Department for Business, Energy & Industrial Strategy

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Glossary

The following terminology is widely used in this report, and is defined below for clarity.

Load Factor: the ratio of the amount of electricity produced by a wind farm to its total potential, based on nameplate capacity, over a period of time (usually one year, to account for seasonal variability in output).

Load Factor is the product of availability (itself a result of the availabilities of the turbines, balance of plant and grid), system efficiency (such as the energy lost in cables), and wind capture, which is dependent on the wind speed, turbine capacity and rotor diameter, and wake efficiency of the wind farm.

It is noted that Load Factor may also be referred to as "Capacity Factor"; the terms are considered interchangeable.

Array efficiency: a measure of the amount of energy lost within the wind farm because of wake effects, which reduces the actual production from a wind farm compared to its theoretical production based on wind speed and turbine power curve.

Wake effect: wind turbines extract energy from the wind and downstream there is a wake from the wind turbine where the wind speed is reduced. As the flow proceeds downstream, there is a spreading of the wake and the wake recovers towards free stream conditions. The wake effect loss is the aggregated influence on the energy production of the wind farm which results from the changes in wind speed caused by the impact of the turbines on each other.

Irregular layout: a wind farm in which turbines are not arranged in straight lines or regular grids but instead are positioned independently of one another, usually to maximise project economics by increasing array efficiency.

Significant wave height: for marine access, sea-state during transfer onto the structures is usually the primary determining factor, typically quantified in terms of significant wave height (Hs) in units of metres. The significant wave height is traditionally defined as the mean wave height (trough to crest) of the highest third of the waves; it was intended to mathematically express the height of waves as estimated by a trained observer.

OFTO: the UK Offshore Transmission Owner (OFTO) regime refers to the offshore wind farm transmission assets at 132kV or above.

1 EXECUTIVE SUMMARY

BEIS has identified the need for improved long-term risk management of the offshore wind Load Factor (LF) assumptions used in its modelling of UK offshore wind farms. The purpose of the work was to facilitate better understanding of LF technology learning rates in offshore wind technologies and hence allow better predictions of long-term energy production potential for deployment on UK offshore wind farms.

The following methodology for the identification and assessment of the technologies as part of the research was developed. For each technology, the methodology was focused on the estimation of the impact of the technology on Load Factor, the timeframe for commercial use of the new technology on operational offshore wind farms and the impact of the technology on project costs.

A review of current offshore wind technologies, and identification of future technologies, was then completed. Based on an analysis of current operational offshore wind farms and on publicly-available information, Load Factors ranging from 39% to 47% have been identified. It is noted that some variation in Load Factor would be expected due to the differing turbine technology deployed on the projects.

A number of future technologies have been identified and described in this report, including the current status and various stakeholders, with a focus on future offshore wind technology which may offer potential commercial viability by 2035. It should be noted that not all of these technologies are likely to achieve commercial deployment, particularly in the light of recent cost of energy reductions achieved by conventional offshore wind projects. However, it is also worth noting that development and deployment of novel future technologies could be best facilitated by a strong home market which favoured indigenous developments.

Improvements in Load Factor from future offshore wind farms are expected to result from the deployment of the next generation of larger offshore wind turbines, together with more advanced wind farm design and control; the combination of increased hub height and reduced wake losses result in increased energy production and therefore higher Load Factor. The magnitude of each individual improvement is relatively small, in low single-digit percentage points, although the aggregate impact will be more significant; these improvements are expected in the next generation of wind farms, which will enter operation in the mid-2020s. These technologies will also contribute to the continuing reduction in the cost of energy from offshore wind, which has seen significant reductions in recent years.

Load Factor is also expected to show a positive trend via increases in turbine and project availability arising from improved operations and maintenance performance, driven by improved accessibility to turbines for technicians to undertake maintenance. Existing offshore wind farms are already starting to revise O&M strategies to take advantage of new technology, and future projects are expected to learn from these improvements to achieve higher availability from entry into service. Improvements in availability are estimated to add up to two percentage points to Load Factor.

There are also a number of more radical technologies proposed for offshore wind, that are in earlier stages of technological and commercial development; these include two-bladed turbines, alternative turbine technologies such as vertical axis turbines, and floating foundations. These are not expected to gain a significant foothold in the UK offshore wind market in the timeframe of this study, which is to 2035, due to both the extent of technical development required and the inherent competition with incumbent technologies.

Offshore wind has been one of the most significant industrial success stories of the early 21st century, achieving rapid deployment and cost reduction to become a mature asset class and contribute a significant proportion of the UK's electrical energy supply. This success is expected to continue, driven by a combination of new and proven technologies and practices, with overall offshore wind Load Factors expected to increase and costs to decrease.

A survey of industry personnel was undertaken, to identify industry expectations and projections with regard to future offshore wind technology and its effects. The results from the scenario modelling were referenced in the survey, and the key results from the survey are summarised in this report. The main conclusions from the survey are in broad alignment with the modelling results, with project Load Factors expected to increase to over 50% (for a project with mean wind speed of 10m/s; specific projects in locations with better wind resource would be expected to exceed this value) in the period to 2035, primarily due to the deployment of larger and more efficient turbines and improved project design and operation. The industry also expects cost of energy to continue to fall in this period, albeit at a lower rate than has occurred to date. Overall, the industry expects that evolution of existing technologies will dominate in the UK market, over potential disruptive technologies.

The onshore and offshore wind industries use largely-similar technologies, allowing for environmental and logistical variation, and it is expected that some future technologies will be applicable to both sectors. A qualitative assessment of the potential for the offshore wind future technologies previously identified to be transferred to the onshore wind industry, and a general commentary on future technologies for onshore wind, has been described.

Many of the future technologies identified are specific to offshore wind, and therefore are not directly applicable to onshore projects – advanced vessels, for example. However, more general wind industry technologies are expected to be applied to future projects both onshore and offshore, contributing to the continuing improvements in reliability, costs and energy production that are expected to occur in both onshore and offshore wind over the forthcoming two decades.

2 INTRODUCTION

On behalf of The Department for Business, Energy & Industrial Strategy ("BEIS"), research has been undertaken into future technology changes and trends in the major technologies in offshore wind.

BEIS has identified the need for improved long-term risk management of the offshore wind Load Factor (LF)[1] assumptions used in its modelling of UK offshore wind farms. The purpose of the work was to facilitate better understanding of Load Factor technology learning rates in offshore wind technologies, and hence allow better predictions of the long-term energy production potential of offshore wind. The study also sought to assess levelised cost of energy (LCoE) from future offshore wind farms, taking into account the continued industry drive to reduce costs and technological development focus on cost reduction, rather than Load Factor.

This study comprised the following steps:

- Review of current technology and assessment of representative UK offshore wind Load Factor;
- Identification of future offshore wind technologies, with the potential for commercial deployment in the period to 2035;
- Assessment of the potential impact on Load Factor and Cost of Energy of each technology, through comprehensive modelling of a hypothetical offshore wind farm;
- Survey of industry stakeholders, to obtain industry opinion on future technologies and validation of the modelling results;
- Assessment of the potential for transfer of the identified technologies to the onshore wind industry;
- Estimation of the effect of technological development on Load Factors of UK offshore wind farms in the period to 2035.

This report summarises these steps, detailed in separate sections to describe the study and its results.

[1] LF in this context is understood as a ratio of electricity produced by a wind farm to its total potential (based on name plate capacity registered with the authorities) during a year.

3 BOTTOM-UP LOAD FACTOR ESTIMATION METHODOLOGY

This scope of work builds on the Review of Renewable Electricity Generation Cost and Technical Assumptions - Study Report /1/ which BEIS currently uses for future Load Factor assumptions.

The scope of work investigated the potential for new technology and improvements or upgrades to existing technology to increase Load Factors for both existing and new offshore wind projects in the timeframe from 2015 to 2035.

For each technology, the methodology focused on the estimation of the impact of the technology on Load Factor, the timeframe for commercial use of the new technology on operational offshore wind and the impact of the technology on project costs.

The technologies considered in this study were identified through industry engagement and considered technologies which can be applied to new and operational offshore wind farms.

3.1 Methodology

The methodology used to identify and assess the technologies from 2015 to 2035 is detailed in this section.

The Review of Renewable Electricity Generation Cost and Technical Assumptions - Study Report /1/ was used as input to this study, in parallel with a review of current operating offshore wind farm projects. This scope of work formed the base case for the current technology Load Factor and costs, against which the estimated improvements in Load Factor and variation in costs have been benchmarked.

The identification of future offshore wind technology focused on research into the potential for offshore wind technology to yield Load Factor improvements, in the period to 2035. This involved consideration of new and upcoming technology in offshore wind, including discussions with the offshore wind industry and relevant research organisations (see Section 8.6), to identify technologies under development that could be implemented on commercial projects in the timescales indicated. This covered both improvements to existing technology and new 'disruptive' technologies which may result in an improvement in Load Factor.

The study has produced a method for estimating future Load Factors and uncertainties which can be updated as assumptions change. The methodology focused on the impact of the technology on Load Factor, the timeframe for commercial deployment of the technology on operational offshore wind farms, and the impact of the technology on project costs.

3.2 Review of current technology

BEIS is currently using the Review of Renewable Electricity Generation Cost and Technical Assumptions - Study Report /1/ to provide Load Factor and cost as inputs to internal modelling of offshore wind.

Therefore, the 2015 Load Factor and cost assumptions have been updated in this report, based on analysis of the most recent operational UK offshore wind farms. These results form the base case for current offshore wind farm technology, against which the future technology improvements can be benchmarked.

The review of Load Factor and costs utilised recently-commissioned offshore wind farms. The following wind farms were chosen, to reflect a range of wind turbines and turbine technologies:

- Ormonde: 150 MW (30 x Senvion 5M), commissioned in 2011;
- Sheringham Shoal: 316.8 MW (88 x Siemens SWT-3.6-107), commissioned in 2012;
- Humber Gateway: 219 MW (73 x MHI Vestas V112-3.0MW), commissioned in 2015;

- Westermost Rough: 210 MW (35 x Siemens SWT-6.0-154), commissioned in 2014;
- Burbo Bank Extension: 254 MW (32 x MHI Vestas V164-8.0MW), commissioned in 2016.

3.2.1 Update to recent offshore wind Load factors

A high-level analysis was undertaken of publicly-available Ofgem production data from the identified operational wind farms, to establish a representative long-term average Load Factor for wind farm technology in the period 2015 to 2017. The Load Factor for the first operational years was corrected in accordance with typical ramp-up rates observed in the industry.

When assessing the high-level production data over a short period of operation, there are key factors which can result in higher or lower wind farm production than expected over the lifetime; these factors may result in a bias in the estimation of Load Factor. The two main factors which could result in a bias are wind speeds and significant operational issues over the period analysed.

Based on the approach used in the DNV GL study "Validation of 25 offshore pre-construction energy forecasts against real operational wind farm data" /3/, adjustments were applied to the production data to remove bias due to high and low wind speed periods over the period analysed and remove significant short-term operations issues, such as export cable failures.

Example results, where the bias due to wind speeds over the operational period have been corrected for, are shown in Figure 3-1 below. Example results for removal of significant operations issues are shown in Figure 3-2 below. As shown in Figure 3-2, short term operations issues have been observed in UK operational offshore wind farms, which have resulted in average 5% losses in production. Analysis on recent offshore wind farms have shown a significant reduction in operational issues and this was summarised for the period 2015 to 2017.

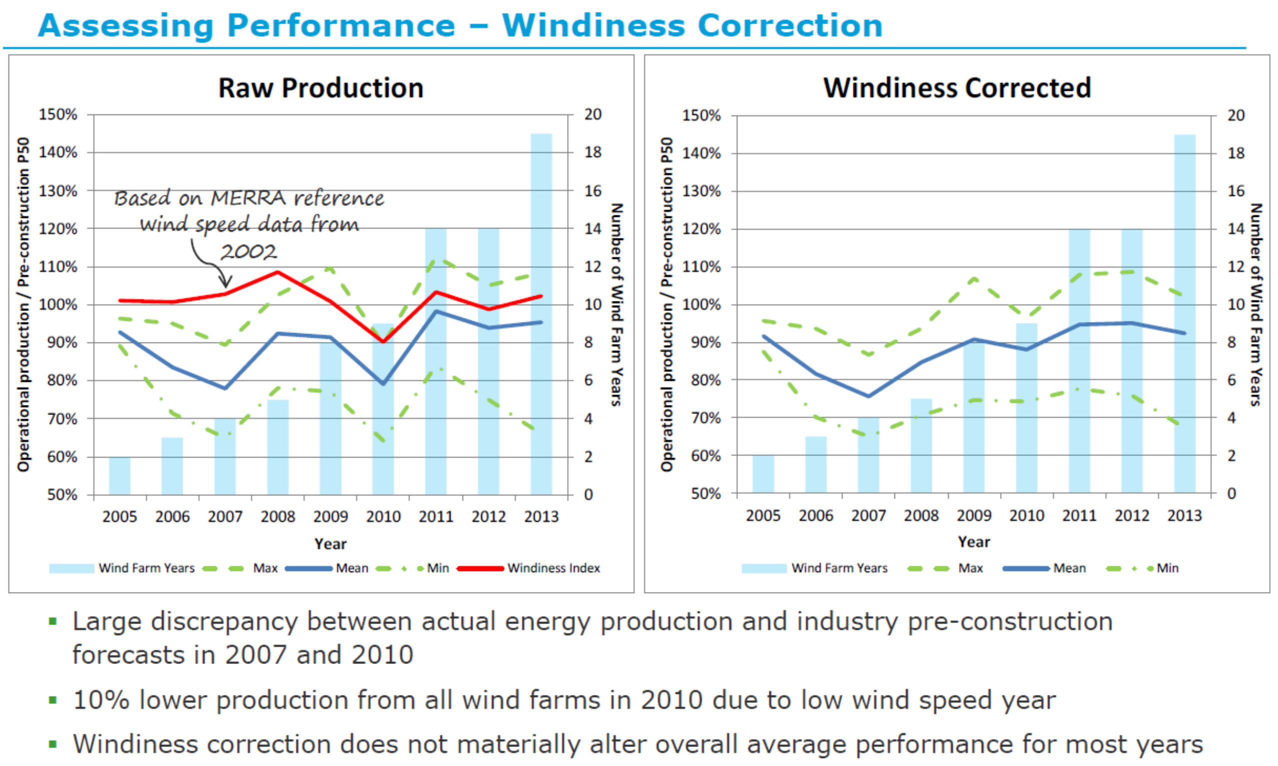

Figure 3-1 Assessing performance - windiness correction

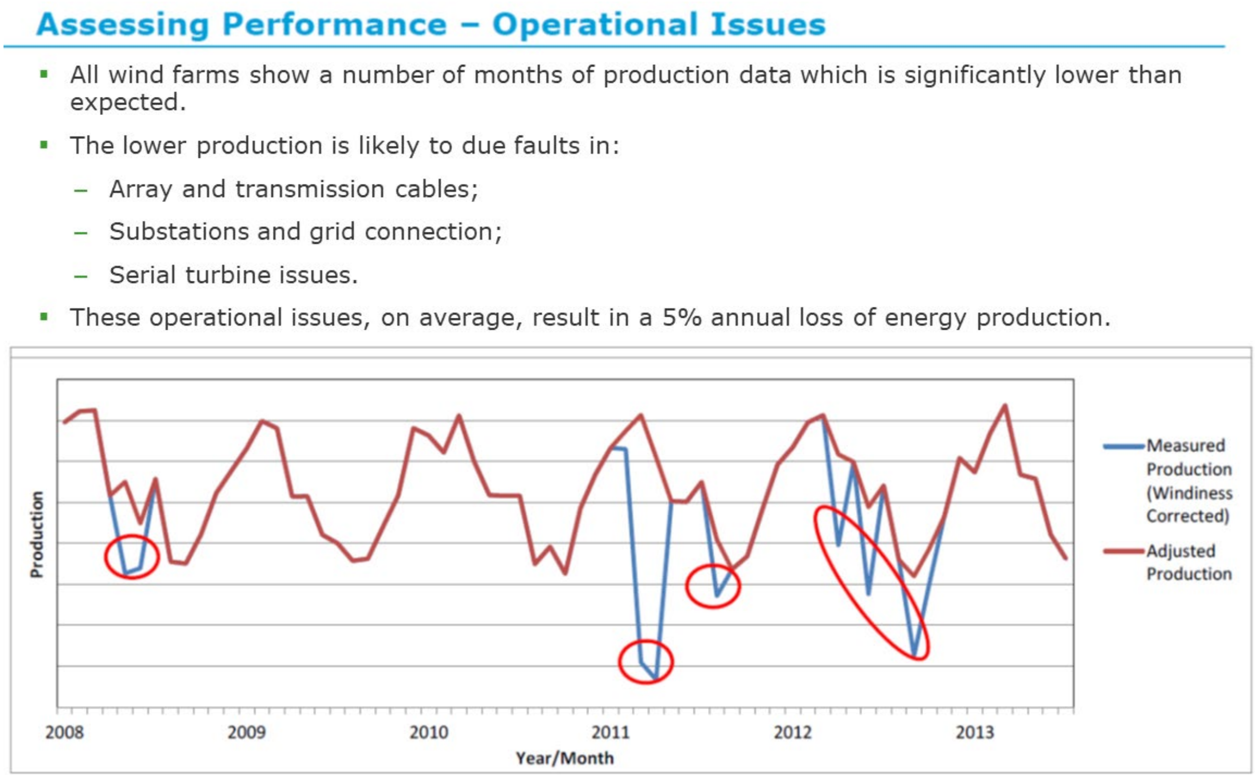

Figure 3-2 Assessing performance - operational issues

3.3 Identification of future technology

The identification of future offshore wind technology focused on research into the potential for offshore wind technology Load Factor improvements up to 2035. This involved consideration of new and upcoming technology in offshore wind, including discussions with the offshore wind industry (developers and OEMs) and relevant research organisations, to identify technology under development that might be implemented on commercial projects in the timescales indicated.

The technology identification has focused on both advances in existing technology and new 'disruptive' technologies which will result in an improvement in Load Factor to offshore wind farms.

Based on a high-level review of publicly-available information, the following categorisations of offshore future technology have been used for this study:

Wind turbine technology

- 10MW+ wind turbines;
- Two bladed wind turbines;
- Turbine performance improvements (Hardware and software):
  - Including impact of turbine drivetrain, geared and non-geared transmission systems;
  - Blade aerodynamic performance, materials and construction;
- Blade extensions;
- New turbine technology (kites and 50MW folding turbines, multirotor, vertical axis);
- Offshore wind turbines from Asian OEMs.

Operations and Maintenance technology

- Service Offshore Vessels and Walk to Work;
- Other vessel-based wind turbine access solutions;
- Helicopter access;
- Highly capable Crew Transfer Vessels.

Wind Farm design and technology

- Floating wind turbine support structure;
- Wind farm control;
- Layout design;
- Electrical transmission system.

3.4 Bottom-up Load Factor modelling

Modelling of future offshore wind farms was undertaken, to assess the impact of each future technology on Load Factor and/or cost of energy. The models used account for turbine size and configuration, blade design, array efficiency, structural design, and operations and maintenance and availability, to comprise a comprehensive model of a hypothetical wind farm within consistent parameters to enable like-for-like comparison.

Load Factors and cost of energy have been estimated using a combination of proven industry modelling tools, comprising:

- Advanced bottom-up wind farm technology modelling and optimisation tool;
- Industry-leading offshore wind farm energy modelling software;
- Industry-standard aero-elastic wind turbine design software; and
- Offshore wind farm operations planning and optimisation tool.

The modelling approach involved the following steps:

- Bottom-up modelling of the assumed turbine, which derived the physical dimensions of the key components in the turbine, such as the mainframe, bearings, hub, drivetrain and blades. The masses of the components was then used to calculate supply cost for each element, and additional factors applied to account for supplier overheads, facilities, profit etc. The sum of these costs comprised the supply cost of the turbines, multiplied by the number of turbines to produce total WTG CapEx.
- The turbine modelling also output turbine loads, which were used to approximate foundation design and in turn calculate foundation mass. Steel fabrication unit costs were then used to calculate foundation CapEx, for primary and secondary steel as required; in addition, foundation mass influenced installation vessel selection and hence installation cost.
- Probabilistic time-domain wind farm O&M modelling, taking into account number and configuration of turbines, assumed site characteristics and turbine reliability, was used to estimate annual OpEx costs and project technical availability. Similar modelling was also used to assess the impact on OpEx (and hence on Load Factor and cost of energy) of different O&M technologies.

- Based on the configuration, physical dimensions of the key components and performance characteristics of the wind turbine the power curve was modelled. The power curve modelling is based on the following items:
    - Aerodynamic performance of the wind turbine blades;
    - Dimensions of the wind turbine blades;
    - Rotational speed of the wind turbine;
    - Size of the wind turbine generator;
    - Wind turbine control system;
    - Mechanical and electrical losses within the wind turbine;
    - Air density and turbulence atmospheric conditions.
- Modelling of annual energy production (AEP) using industry-leading software, based on the wind conditions and turbine power curve. The energy production of modelled turbines in a hypothetical wind farm was combined with project factors such as technical availability to capture the impact of each technology.
- Calculation of levelised cost of energy, using the modelled CapEx, OpEx and AEP via a simple discounted cash flow model.

The modelling was used to compare each technology to the updated base case Load factor and costs for 2015, as detailed in Section 3.3. Results are reported in Section 8.5, for the period 2020 to 2035.

4 REVIEW OF CURRENT OFFSHORE WIND TECHNOLOGY

The scope of work investigated the potential for new technology and improvements or upgrades to existing technology to increase Load Factors for both existing and new offshore wind projects in the timeframe from 2015 to 2035. Additionally, for each technology, the impact of the technology on costs was considered.

The review was split into three categories, to align and focus on related technologies; these categories are:

- Wind turbine technology;
- Wind farm design;
- Operations and maintenance (O&M) technology.

This section details the review of current offshore wind technologies. Subsequent sections describe future technologies, with a focus on the impact of the technology on Load Factor, the timeframe for commercial use of the new technology on operational offshore wind, and the impact of the technology on project costs.

4.1 Current offshore wind technology

The following section summarises the current technologies deployed at utility-scale offshore wind farms globally.

4.1.1 Introduction to the technology

4.1.1.1 Turbine technology

Offshore wind turbines originally evolved from onshore machines, adapted to the offshore environment, without the geometric and mass constraints imposed by road transport for onshore wind. However, offshore turbines are now dedicated designs, considering the different performance parameters offshore, as well as the requirement for factors such as increased corrosion protection and system redundancy.

The offshore wind industry is currently dominated by three-bladed, horizontal-axis, upwind turbines mounted on tubular steel towers and foundations fixed to the seabed; current state-of-the-art offshore wind turbines generate between 7MW and 9.5MW per turbine, with rotors of approximately 150m to 170m diameter. The offshore wind industry has seen rapid growth in turbine size; less than five years ago, the market was dominated by turbines in the 3-4MW class. This increase in turbine scale has been the primary driver behind the recent rapid reductions in the cost of energy from offshore wind.

Increasing turbine rotor diameter typically yields increased load factors, as the larger turbines access increased wind speeds through their higher reach, whilst a wind farm comprising fewer, larger turbines would also be expected to demonstrate increased array efficiency and hence load factor.

Current offshore wind turbines use both geared and direct drive drivetrains, varying by manufacturer. The geared designs have moved to medium-speed “hybrid” systems to improve reliability, whilst direct drive systems are claimed by the OEMs to be both lighter in weight (which brings advantages during both installation and O&M) and more reliable due to fewer moving parts. Improved reliability results in increased availability, and hence increased load factor.

4.1.1.2 Wind farm design and technology

Offshore wind farms to date have typically been designed in a grid layout, with regular spacing between turbines; this spacing may vary within a wind farm, as larger spacings are typically employed in the direction of the prevailing wind to maximise array efficiency and hence energy production. Grid layouts support search and rescue requirements for clear paths through the wind farm, but do not offer the optimum array efficiency and hence result in a slightly lower Load Factor than may otherwise be possible. Irregular layouts, in which turbines are not arranged in straight lines or regular grids but instead are positioned independently of one another, are becoming common on the most recent projects, and can offer increased array efficiency and hence higher Load Factor. It should be noted that wind farm developers optimise the project configuration for overall project economics, and therefore the absolute highest possible Load Factor may not be achieved; for example, very large inter-turbine spacing may increase array efficiency slightly, but at the cost of significant CapEx increase for intra-array cabling, and are therefore not employed.

The energy produced by offshore wind turbines is typically collected by medium-voltage intra-array cables, which are laid out in strings or loops to connect to neighbouring turbines and, eventually, to an offshore substation platform. This platform supports electrical equipment, including transformers, which steps up the voltage to enable energy to be transferred to shore at high voltage, which reduces electrical losses and increases efficiency. The substation platform exports energy via high-voltage submarine export cables, which run to shore and on to the grid connection point, where the energy is transmitted into the national transmission system. The electrical infrastructure of offshore wind farms is highly efficient; technical advancements may be more concerned with reducing cost and increasing reliability, which in turn would contribute to increased Load Factor.

4.1.1.3 Operations and maintenance technology

Current and planned offshore wind farms around the world are operated and maintained through a variety of different strategies and access methodologies. Such access strategies are predominantly concerned with the transportation of technicians, parts and equipment from an operations and maintenance base and their subsequent safe transfer between a marine vessel and the offshore structures.

Until recently, offshore wind O&M strategies were primarily based on the use of Crew Transfer Vessels (CTVs); these are relatively small (below 30m in length) workboats, which are based in port and transit to the windfarm each working day. CTVs are fast and versatile, and able to transfer technicians to turbines in sea states with wave heights of up to approximately 1.5m Hs – the use of a CTV-based O&M strategy, therefore, achieves reasonable technical availability, contributing to the baseline Load Factors of established offshore wind farms. Sea states exceeding 1.5m Hs would be expected to occur approximately 15% to 30% of the time at a typical UK offshore wind farm.

Recent offshore wind projects have started to use alternative or complementary O&M strategies, using either helicopter access or more advanced vessels, or both – please see Section 7 for further details. Both methods offer technician access in more onerous conditions, and hence contribute to increased technical availability (in comparison with CTV-based strategies) and hence increased Load Factors.

Whilst modern offshore wind farms typically employ condition-based monitoring, which is used to inform scheduled maintenance strategies, this does not yet enable the overall maintenance requirement to be reduced. However, modern offshore wind SCADA (Supervisory Control and Data Acquisition) systems offer the opportunity to reduce the maintenance burden through the use of “big data”, in which wind turbine performance and monitoring data is assessed to identify potential issues ahead of component failure; once identified, these issues can be corrected at minimal lost production and cost to the project. An example of such data collection would be the monitoring of drivetrain temperatures, where increased temperature may indicate insufficient lubrication and continued operation without rectification could cause bearing failure. This approach is not yet in widespread use, but is expected to gain traction in the near future; it offers the opportunity to reduce operational expenditure, although its overall impact on the Load Factor of individual projects is expected to be minimal.

4.1.2 Industry stakeholders

The primary industry stakeholders, with respect to the technologies investigated in this report, are the major offshore wind developers and the turbine OEMs; other industry stakeholders include balance of plant suppliers and installation contractors.

Developers have historically been willing to adopt new technology and new turbine variants in the drive to lower costs and improve project performance, and would be expected to continue this approach as turbines develop further. There are risks associated with the adoption of new technology, which may manifest as increased financing costs due to the risk premium related to the unproven technology; however, historically, the economic benefits offered by technological developments have outweighed the risks. Offshore wind has matured such that it now offers stable, relatively low margin but low risk returns. Offshore wind project development carries inherent risks, but these are now limited and are mitigated early in development.

4.2 Analysis of current technology Load Factors

A high-level analysis was undertaken of publicly-available OFGEM production data from the identified operational wind farms, to establish a representative long-term average Load Factor for wind farm technology in the period 2011 to 2017.

The following recently-commissioned offshore wind farms have been selected for the analysis based on data quality, to reflect both small and large capacity wind turbines and a range in technology:

- Ormonde 150 MW (30 x 5M Senvion) commissioned in 2011;
- Sheringham Shoal 316.8 MW (88 x SWT-3.6-107 Siemens) commissioned in 2012;
- Humber Gateway 219 MW (73 x V112-3.0MW MHI Vestas) commissioned in 2015;
- Westermost Rough 210 MW (35 x SWT-6.0-154 Siemens) commissioned in 2014; and
- Burbo Bank Extension 254.2 MW (32 x V164-8.0MW MHI Vestas) commissioned in 2016.

4.2.1 Method Overview

The analysis of current offshore wind Load Factors was undertaken through the following method:

- Monthly production data from OFGEM, the UK electricity and gas market regulator /4/ was obtained, for the relevant offshore wind farms, along with the commissioning dates of these projects /5/.
- When assessing the high-level production data over a short period of operation, there are key factors which can result in higher or lower wind farm production than expected over the lifetime. These factors may result in a bias in the estimation of Load Factor. The two main factors which could result in bias are wind speeds and significant operational issues over the operating period.
- Adjustments to the production data have been applied, to remove bias due to wind speeds over the operational period, ramp up during the first operational years and significant short-term operational issues.
- The adjusted production data was then used to estimate Load Factors for the current offshore wind technology.

4.2.1.1 Windiness correction

An exercise has been undertaken to quantify and remove the influence the windiness of the operational years has on the observed results. Modern Era Retrospective-analysis for Research and Applications, Version 2 (MERRA-2) data was extracted at a number of locations of interest for this purpose; MERRA-2 data is regularly used in commercial energy yield assessments of operational wind farms and typically correlates well with offshore wind farm data. The MERRA-2 data set has been produced by the National Aeronautics and Space Administration (NASA) by assimilating satellite observations with conventional land-based meteorology measurement sources using the Goddard Earth Observing System Data Assimilation System Version 5.12.4 (GEOS-5.12.4) atmospheric data assimilation system /6//7/. The analysis is performed at a spatial resolution of 0.625° longitude by 0.5° latitude.

The consistency of the MERRA dataset across the UK was investigated /8/ and on the basis of these investigations the long-term reference period considered for the MERRA dataset is from January 1996 to the present.

For the periods where monthly production data is available for the five recently commissioned offshore wind farms, the normalised production was compared against the monthly wind speed data. A summary of the raw monthly production and wind speed data is shown in the figure below. The figure shows good agreement between the average wind farm production and wind speed data, with significant variation in the range of production across the five wind farms. The range of production data across the five project is highlighted by the minimum and maximum values shown in the figure below. For example, in early 2015, late 2016 and late 2017 there is a significant variation in the minimum production from a single wind farm to the average of the five wind farms. It is understood that this variation in minimum production is due to operational issues in these months at two of the five projects; these operational issues are discussed in the following section.

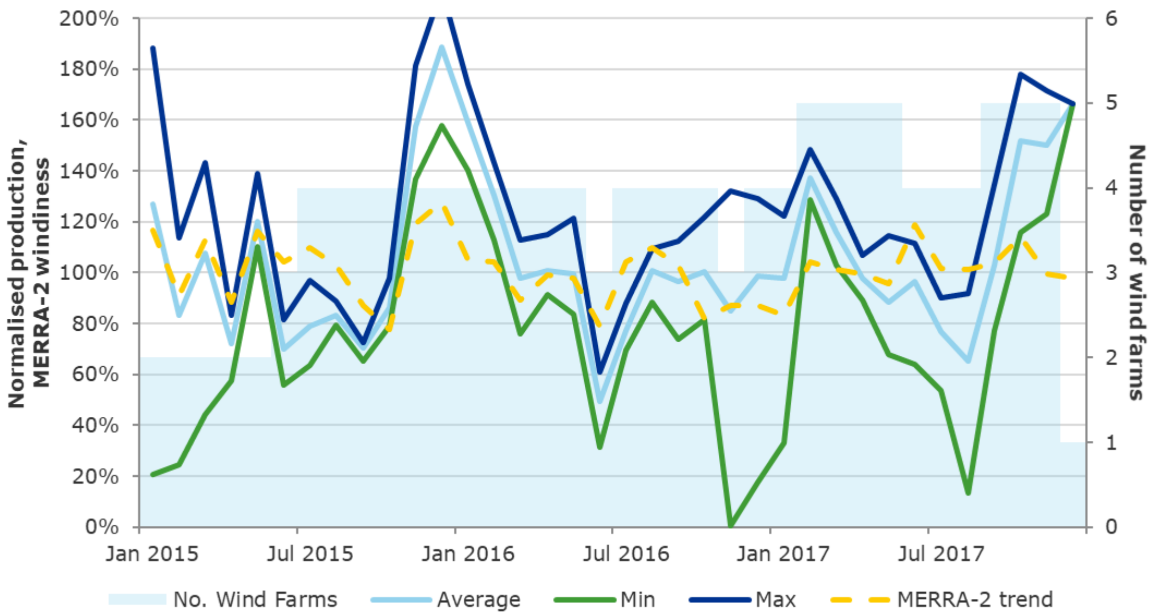

Figure 4-1 - Trend of raw production data

The production data from the five recently commissioned offshore wind farms, has been corrected for the variation in wind speed to remove bias from the estimated Load Factor for each wind farm. This has been carried out by comparing the wind speed in a given month to the long-term wind speed for that month for each wind farm. The correction therefore removes the impact of a given month being more or less windy than the long-term average for that month, but does not remove the seasonal variation between different months within the year. The resulting trend in measured production by month from 2015-2017, corrected for windiness of the operational periods, is shown in the figure below.

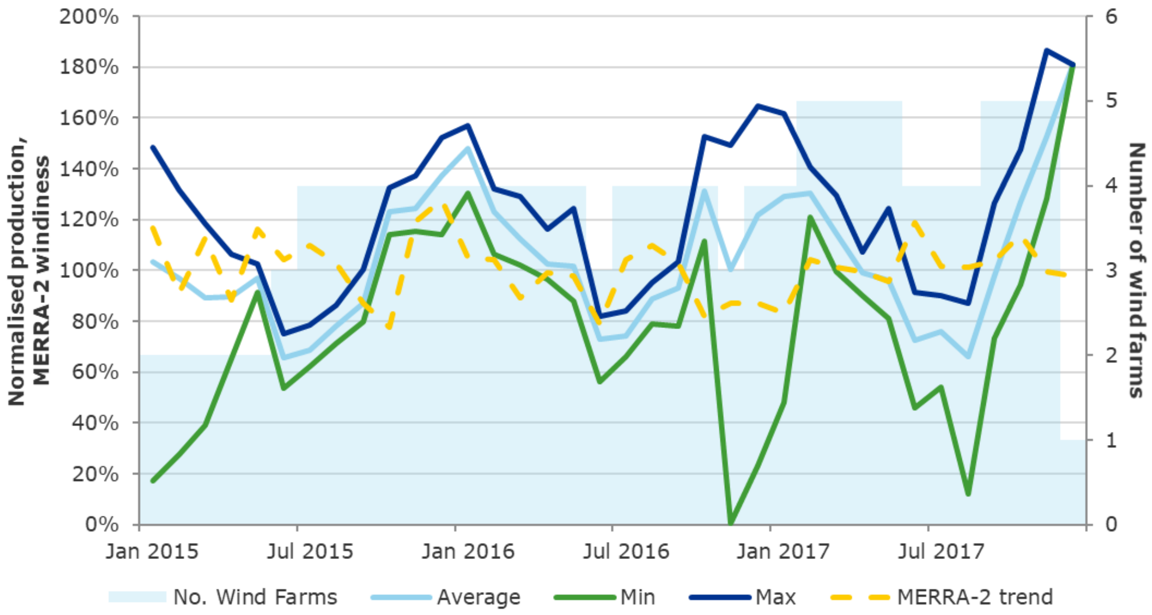

Figure 4-2 - Trend of production data corrected for windiness

4.2.1.2 Operational issues

In the absence of detailed availability reports for each wind farm, a high-level review based on the monthly production data available was undertaken, as described below, to identify significant short-term operational issues.

For each wind farm, actual monthly production was compared with the expected production, based on the windiness of the period, to identify any significant operational issues. An example of one wind farm project is shown in the figure below, which clearly highlights an operational issue in late 2017, which is also identified in Figure 4-3, where the production from this wind farm is significantly lower than the average of all five wind farms.

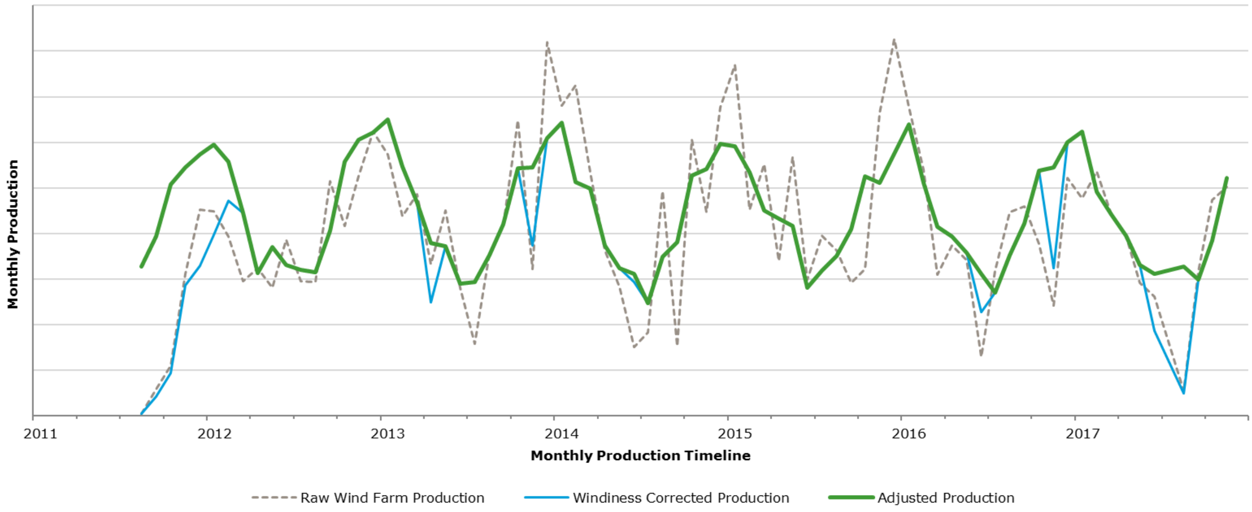

Figure 4-3 Operational issues observed at an example wind farm

The comparison in the example shown above highlighted several months where the actual production was significantly lower than expected. It is assumed that these deviations are due to various sources of downtime such as cable outages or other issues with Balance of Plant or defects during the first years of operation. Based on the information available for the high-level analysis, no additional adjustments have been made for periods of high or low wind farm availability.

In order to quantify the magnitude of the impact that these operational performance events have on overall performance adjustments were applied to the production data. The time series of production data corrected for operational issues is also shown in Figure 4-3 for the example wind farm project. The variation in wind farm production for all five projects, after correction for operational issues and windiness, is shown below. The results show good agreement between each wind farm and across the period.

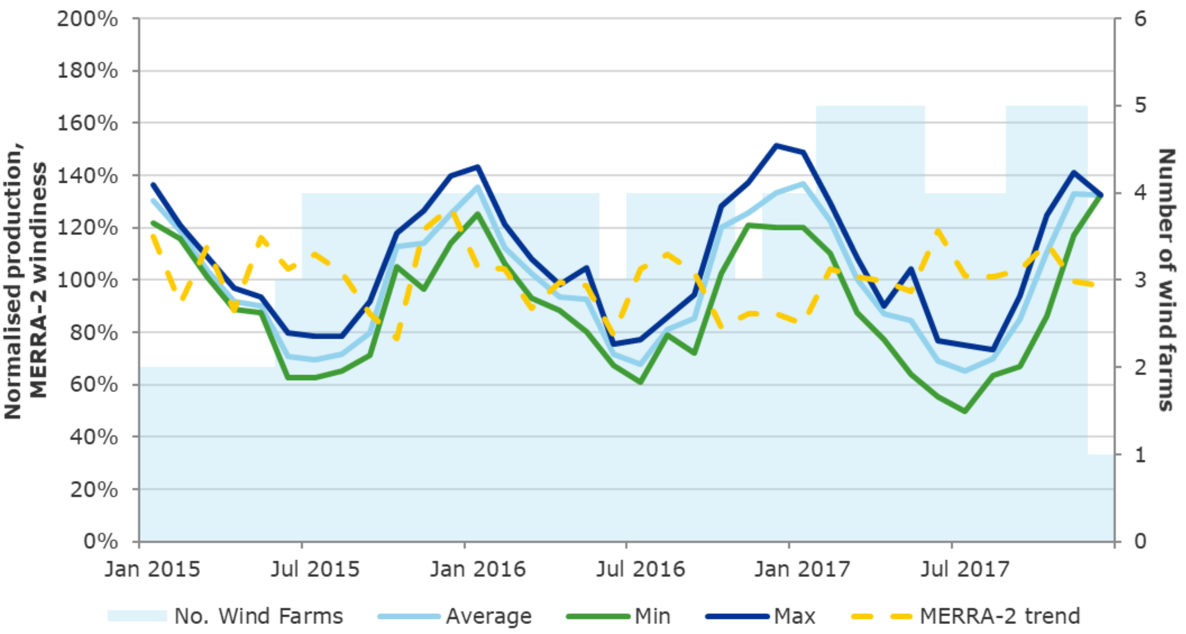

Figure 4-4 - Trend of production data corrected for windiness and operational issues

4.2.2 Results

Based on the analysis carried out, the following monthly Load Factors were calculated for the wind farms considered. The reported annual Load Factors are shown including adjustments for the coverage of months in each year in order to remove bias due to operational period. Based on the information available for the high-level analysis, no additional adjustments have been made for periods of high or low wind farm availability. The overall averages are based on the mean of the monthly mean load factors.

	Burbo Bank Extension	Humber Gateway	Ormonde	Sheringham Shoal	Westermost Rough
2011			41%		
2012			41%	38%	
2013			42%	38%	
2014			40%	40%	47%
2015		42%	41%	39%	45%
2016	39%	44%	41%	41%	48%
2017	39%	44%	38%	40%	49%
Annual Average	**39%**	**44%**	**41%**	**39%**	**47%**

Table 1 – Annual load factors of selected wind farms

Wind Farm	**Years of data**	**Average annual load factor**	**Turbine technology**	**Power density [kW/m^2]**
Burbo Bank Extension	2016 – 2017	39%	MHI Vestas V164-8.0MW	0.38
Humber Gateway	2015 – 2017	44%	MHI Vestas V112-3.0MW	0.30
Ormonde	2011 – 2017	41%	Senvion 5M (rotor diameter 127m)	0.39
Sheringham Shoal	2012 – 2017	39%	Siemens SWT-3.6-107	0.40
Westermost Rough	2014 – 2017	47%	Siemens SWT-6.0-154	0.32

Table 2 – Summary of wind farm load factors and turbine technology

It can be seen that there is some variation in load factor between the projects, with the highest load factors seen for the Humber Gateway and Westermost Rough wind farms. The load factors for Humber Gateway and Westermost Rough are in line with expectations given the turbine technology used on these projects. The MHI Vestas V112-3.0MW and Siemens SWT-6.0-154 wind turbine technology have a lower power density compared to the wind turbine technology used at the other projects, as shown in the figure below. Power density is a measure of the relationship between the swept area of a wind turbine and its generator capacity; turbines with a low power density have a comparatively larger rotor relative to the nameplate capacity, which can result in better low-wind performance and hence higher load factors.

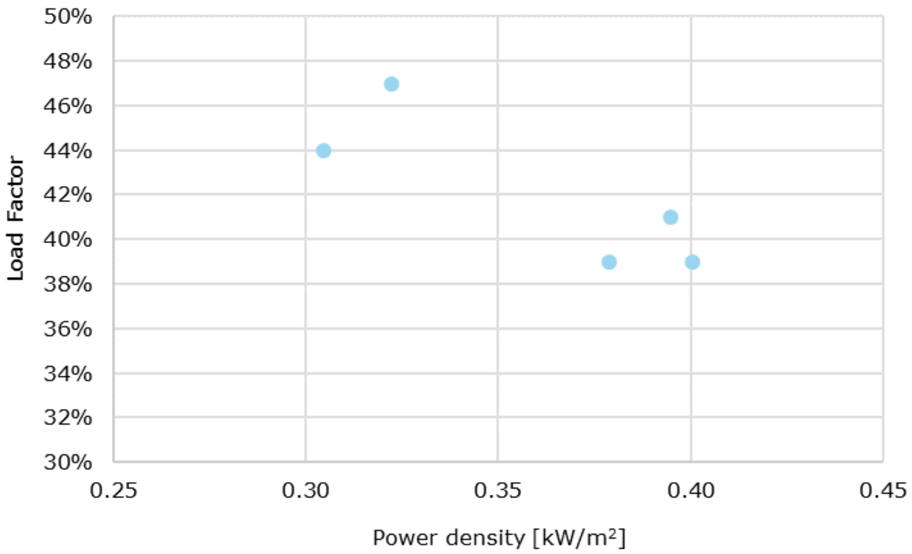

Figure 4-5 – Power density vs load factor

The results reflect the different configurations of turbines used in each project, as the correction for windiness removes the impact of variable resource and hence highlights the relative performance of the turbines. The highest Load Factors are achieved by the turbines which feature the lowest power density, where the better low-wind performance manifests as increased Load Factor; the converse is also shown above, in which the projects featuring turbines with higher power density exhibit lower Load Factors.

However, whilst Figure 4-5 shows some correlation between Load Factor and power density, there is some variation in the Load Factor of projects which feature turbines of similar power density. This is due to variation between individual wind farms, in terms of both design and operation – for example, the Humber Gateway and Westermost Rough wind farms are located in close proximity and feature turbines of similar power density; however, Humber Gateway is more densely-packed than Westermost Rough and thus incurs increased wake losses (see Glossary), contributing to a reduction in Load Factor. The Load Factors shown above may also be affected by individual project factors, such as local wind resource and project availability, that were not of sufficient resolution to be corrected in the data processing, which accounts for some of the variation between similar projects.

These results highlight some important points with regard to the assessment of future Load Factors: firstly, that turbine power density is significant, as well as generating capacity. The newest and largest turbine in the list of assessed projects is the MHI Vestas V164, at the Burbo Bank Extension wind farm; this project demonstrates the lowest Load Factor of the five projects. Whilst there are other contributing factors, this turbine features a high power density, and therefore would be expected to yield lower Load Factors; future Load Factors will therefore be influenced by the choices of turbine OEMs with respect to power density. Secondly, project design and operation can impact Load Factor through wake efficiency and operation; these factors are discussed further in the following sections.

4.3 Update of recent costs

The review of current technology covers projects commissioned over the period 2011 to 2016; therefore, the offshore wind costs used to assess the cost impact of future technology will be based on the same period. Based on the BEIS Electricity Generation Costs report /9/, a levelised cost of £121/MWh is estimated. The 2016 levelised cost of energy is broadly in line with typical assumptions of the time. However, offshore wind costs have recently fallen significantly, with the award of Contracts for Difference to offshore wind farms at strike prices of £74.75 and £57.50 (in 2012 prices) for delivery in 2021 and 2022 respectively; the primary driver behind this cost reduction has been the evolution of the supply chain, with increased manufacturing capability and improved construction practices. These lower strike prices can now be considered the baseline for UK offshore wind cost (and, for the purposes of comparison, to represent the levelised cost of energy from these projects).

It should be noted that offshore wind cost of energy (and therefore the underlying CapEx and OpEx) has reduced significantly in recent years, and this downward trend is expected to continue – albeit perhaps at a slower pace.

Offshore wind CapEx and OpEx vary between projects, depending on factors such as the size of the wind farm and its distance from shore. For example:

- A wind farm located far from its grid connection point will require a higher proportion of CapEx to be spent on export cabling than one with a shorter export route;
- Locations in deeper water will require larger, heavier and hence more costly foundations than those in shallower seas;
- Difficult ground conditions may require more costly foundation concepts or designs, such as drilled piles, increasing installation CapEx;
- Development costs and some electrical infrastructure CapEx do not scale linearly with project capacity, so smaller projects may be expected to exhibit a higher proportion of CapEx in these areas than a larger development;
- Far-offshore wind farms may require costlier O&M methodologies, as shore-based strategies become uneconomic.

5 IDENTIFICATION OF FUTURE WIND TURBINE TECHNOLOGY

This section describes future offshore wind turbine technologies; the technologies identified are those in which significant development effort has been expended by various stakeholders, and which may offer potential commercial viability by 2035. It should be noted that not all of these technologies are likely to achieve commercial deployment, particularly in the light of recent cost of energy reductions achieved by conventional offshore wind projects. However, it is also worth noting that development and deployment of novel future technologies could be best facilitated by a strong home market which favoured indigenous developments. Technology innovation is a primary driver behind cost reductions, and many of the technologies included in this report would be expected to contribute to reduced cost of energy from offshore wind.

Turbine OEMs have also released upgraded versions of existing products, in which either or both of the generator capacity and rotor diameter are increased. These upgrades are typically based on the existing technology of the predecessor product, and hence represent a relatively low-risk approach to increasing turbine size. It is noted that increasing the generator capacity of a turbine without increasing the rotor diameter increases the power density and hence would be expected to reduce the load factor, as the turbine would achieve rated power less often; however, this approach potentially offers the benefit of reduced cost of energy.

5.1 Next-generation (10MW+) offshore wind turbines

5.1.1 Introduction to the technology

Current state-of-the-art offshore wind turbines generate between 7MW and 9.5MW per turbine, with rotors of approximately 150m to 170m diameter. The major turbine manufacturers (Siemens Gamesa Renewable Energy, MHI Vestas, Senvion) are all believed to be developing the next generation of offshore wind turbines, and whilst technical details have mostly not been formally announced, it is believed that these devices will each offer generator capacity in excess of 10MW and rotor diameters in excess of 200m.

In March 2018, GE released details of its next-generation offshore wind turbine /8/: the Haliade-X, which will comprise a 220m rotor and a 12MW direct-drive generator.

Whilst increasing turbine scale brings engineering challenges through, for example, scaling effects that cause the weight of blades to increase in proportion to the cube of their length, it is expected that turbines will continue in the short- to medium-term to grow in both rotor diameter and generator capacity.

Research studies into future turbine technology have been undertaken, particularly with regard to the technological limits to increasing turbine scale. This research suggests that generators of approximately 12MW capacity, and rotors of up to approximately 220m diameter, are technically feasible using current offshore wind turbine technology; beyond these dimensions, new technologies would be expected to be required to enable the development and production of suitable turbine components (rotor hub and mainframe), bearings, drivetrains and blades.

Longer blades result in increased blade root diameter, in order to support the increased loads during operation; the blade root of offshore wind turbines typically does not feature an aerodynamic profile. Some onshore turbines have featured a more aerodynamic profile at the blade root but, due to the low diameter and hence low blade speed at the root, the contribution to turbine performance is minimal; this effect is magnified as turbines increase in diameter and hence rotational speed reduces. However, this effect also means that the energy penalty associated with increased blade root diameter is minimal.

Research results from Innwind EU /11/ have highlighted a notable motivation towards larger turbine scale than is currently employed offshore, due to the way in which turbine mass and support structure stiffness scales; the result is very favourable in terms of machine dynamics and in avoiding interaction between certain rotor frequencies and the support structure frequencies. Accordingly, support structures can be better optimised without the constraint of keeping below certain stiffness values to avoid dynamic issues. This also underlines the need for a more integrated approach to design of turbines and offshore support structures.

5.1.2 Current technology development status

The next generation of offshore wind turbines are currently still in the development and design stage, with prototypes yet to be constructed and tested and serial commercial production still some years away. It is expected that, based on historical trends, an onshore prototype of a new turbine would be installed approximately two years from its announcement, and that commercial operation would be achieved approximately three years after that. Accordingly, the next generation of offshore wind turbines (of which the GE Haliade-X is the first to be announced) are expected to enter commercial service in the mid-2020s, and therefore that one more "generation" of offshore wind turbines would be expected within the timeframe of this study.

It is expected that these turbines will largely build upon existing industry knowledge and practice, and therefore that much of the technology within the next generation of turbines is relatively proven. Accordingly, these machines would be considered to be reasonably well developed, with much of the underlying technology demonstrated in a relevant environment.

5.1.3 Impact of the technology

Increasing turbine rotor diameter typically yields increased load factors, as the larger turbines access increased winds through their higher reach, whilst a wind farm comprising fewer, larger turbines would also be expected to demonstrate increased array efficiency and hence load factor (see Section 6.3 for further discussion of the impact of wind farm layout and array efficiency). Larger turbines are also expected to contribute to further reductions in the cost of energy, which may in turn drive the deployment of increasing volumes of offshore wind.

It is generally assumed that the power density of next generation turbines will be similar to that of current products. Turbine manufacturers may release up-rated versions of existing turbines, in which generator capacity is increased but the rotor remains constant – this has the effect of increasing the power density, and potentially reducing the cost of energy in locations with good wind resource, but at the cost of reducing the load factor of a project using such turbines. This is demonstrated, for example, in the development of the MHI Vestas V164 turbine, which originally featured an 8MW generator and was subsequently increased to 9.5MW; this had the effect of increasing the power density from 379W/m^2 to 450W/m^2.

Previous design studies into next-generation offshore wind turbines consider that large turbines such as the GE Haliade-X are technically feasible (based on the limited information made publicly available to date) from the point of view of both design and manufacturing. The development of very large turbines is limited by key components, such as the pitch bearing (as noted below), although the 220m-diameter rotor of the Haliade-X is expected to within the capabilities of current technology. Application of alternative bearing technology to the pitch bearing will alleviate some of the challenges, with use of roller bearings expected; however, pitch bearings are expected to present significant technical challenges for rotors in excess of approximately 240m diameter, without a step change in rotor design.

Advanced control technology is playing a major role in enabling larger rotors, yet mitigating the associated loads increases. A lot of the advanced control technology centres around capturing data from the turbine (load measurements) or the advancing wind field (LiDAR) and computing this via advanced control algorithms that control blade pitch activity to minimise loading and maximise energy capture. Blades are pitched to control power generation and loads as the turbine approaches rated power; the blades are then feathered (i.e. pitched out of the air flow) to shed excess energy and avoid overload. With ever-increasing rotor size, the methods of achieving blade pitch control response (i.e. pitch motion) are also a subject of a lot of R&D currently with, for example, active trailing edge flaps being investigated (the Innwind EU project), but also considerations about moving the pitch bearings further out down the blade length (pitching a 100m+ blade from its root presents ever-increasing challenges for the pitch bearing). As rotors scale up, the pitch bearing diameter generally scales faster than the blade root diameter. It is clear that innovative rotor technology will play a part in future developments.

It is expected that increases in turbine size will begin to slow, such that turbines of up to perhaps 15MW are expected by 2035 but that significant increases beyond this capacity are considered unlikely. This is due to a number of factors: firstly, further size increases offer diminishing returns in cost of energy, and it may be that, beyond this size, reductions in cost of energy are better served by manufacturing economies of scale and mass production than by further scale increases.

Secondly, the key components which limit turbine size become increasingly significant, requiring more complex and more costly solutions, potentially undoing some of the cost reduction achieved by scale – for example, it is understood that a gearbox suitable for a 15MW+ turbine would be difficult to engineer economically to suitable tolerances, particularly given that as rotor diameter increases, rotational speed decreases and therefore the torque in the drivetrain increases significantly. Direct drive concepts may offer advantages over geared designs at very large sizes, although the main bearing presents technical challenges for direct drive designs.

Thirdly, manufacturing economies of scale reduce with increasing turbine size, as fewer turbines are required to achieve a given installed capacity and hence sales volumes (in number of turbines) drop. This changes the business case for a new turbine, and requires the development expenditure to be amortised over a smaller number of machines, therefore adding cost. This is compounded by the requirement for new testing facilities, as very large turbines may soon exceed the capacity of even the largest current test benches, and the investment in these facilities would have to be included in the business case for the development of a new turbine.

Advanced materials are expected to become more common in very large wind turbines, although are not expected to comprise significant proportions of the overall turbine bill of materials. Rotor hubs are currently cast iron components, and can weigh up to 100 tonnes; very large turbines would require a hub in excess of 200 tonnes, which is considered beyond the capability of the supply chain. Therefore, carbon fibre-reinforced composite hubs have been postulated, which would enable different hub designs and hence different bearing designs. Carbon fibre is also likely to be used in larger blades, where the combination of strength and stiffness enables blade weight to be reduced and pre-bend reduced – pre-bend of very large blades (required to avoid tower impact in high winds) presents a significant manufacturing challenge, with very large facilities required to accommodate pre-bend that can exceed six metres. However, use of carbon fibre in blades will not resolve some of the technical challenges of very large turbines, such as the pitch bearings, as the dominant factor is rotor diameter and loads, which would remain similar even with a stiffer, lighter blade.

Significant changes to turbine tower design or materials are not expected, even as nacelle mass and hub height increase. Wind turbine towers are amongst the lowest-cost mass-produced steel structures, and the relative absence of transportation restrictions for offshore wind mean that tubular-section steel towers are considered likely to remain the most economical option.

5.2 Two bladed wind turbines

5.2.1 Introduction to the technology

Current commercial wind turbines, both onshore and offshore, are predominantly three-bladed designs. However, two-bladed turbines have previously been developed, tested and sold, and advanced two-bladed designs are being developed for the offshore market.

Two-bladed turbines typically exhibit slightly lower efficiency than three-bladed designs; aerodynamic efficiency increases with number of blades, but with diminishing return, and the efficiency penalty for a two-bladed turbine in comparison with an equivalent three-bladed device is approximately 3%. Two-bladed designs are often designed to operate at a slightly higher tip speed ratio, and therefore higher rotational speed, which increases the noise emissions from the turbine; this may be one reason why the three-bladed concept is preferred onshore, but is less of a concern offshore.

Component costs that scale with number of blades will obviously be lower for a two-bladed turbine than its three-bladed equivalent; this may include the cost of the blade itself, as well as the hub and pitch system. In addition, the higher rotational speed may reduce torque in the drivetrain, and enable the use of lighter, less-costly drivetrain components. The complete turbine may also then be lighter, and hence enable savings in tower and foundation design. However, two-bladed turbines exhibit different dynamic behaviour in yawing operations, and hence a more robust yaw system may be required.

Two bladed turbines have historically exploited a teeter hinge type hub (see Figure 5-1) with the objective to reduce fatigue loading on the turbine nacelle structure and drivetrain, however as the size of the rotor scales up, the extreme loads associated with the teeter hinge hitting its limit can start to make the structure extreme loads driven and hence the fatigue load savings have no effect on the structure. Furthermore, with a larger rotor diameter (as for offshore) and hence slower rotor rotational speed, there is more scope for blade pitch control to mitigate the asymmetric loading that would previously have been dealt with by a teeter hinge. Indeed, this is reflected in the design of 2-B Energy where there is no teeter hinge. Removal of the teeter hinge also simplifies the drivetrain; there are fewer components to maintain and less scope for failure.

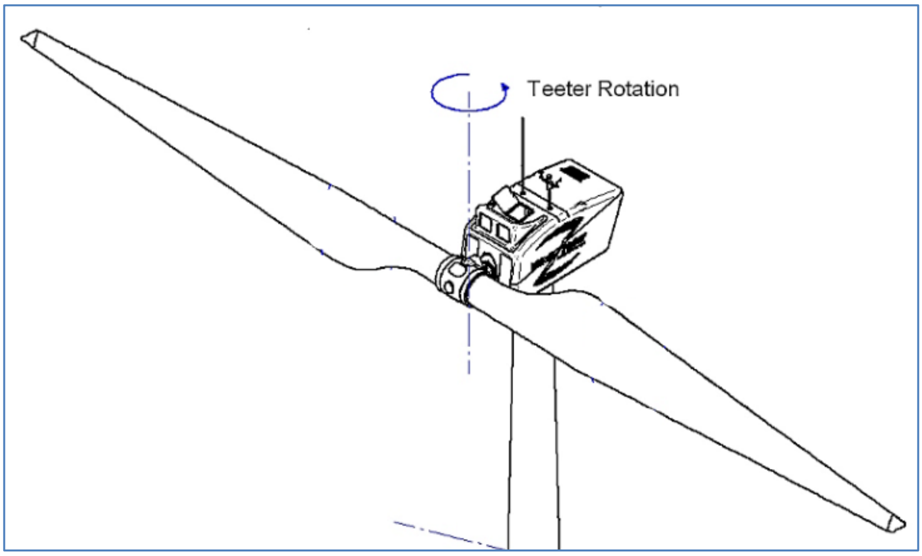

Figure 5-1: Teeter hinge

5.2.2 Current technology development status

A number of two-bladed turbine concepts are understood to be, or recently have been, in development by independent device designers.

Of these, 2-B Energy are the most advanced and the only organisation listed which is currently openly pursuing the two-bladed concept.

The 2-B Energy design is for a 6MW, 140m-diameter, downwind two-bladed turbine on an integrated truss tower and jacket structure; installation takes place with the rotor mounted to the nacelle, in a single lift /13/. A prototype turbine has been installed onshore at Eemshaven in the Netherlands, and 2-B Energy is currently developing a demonstration two-turbine project off Fife, Scotland /14/. Although there are few proponents of the two-bladed turbine, the fact that the 2-B Energy device has achieved successful installation and operation of a prototype puts this concept at a more advanced stage of commercial readiness than many of the technologies outlined in this document.

If two-bladed turbines demonstrate commercial viability, it would be expected that project deployment would follow with the result that the project developers would then become stakeholders – there are few logistical barriers to the construction of projects using two-bladed turbines.

5.2.3 Impact of the technology

The operating performance of two-bladed turbines is well understood, and practical deployment of utility-scale offshore wind farms using two-bladed turbines would be expected to exhibit load factors slightly lower than their three-bladed competitors due to the lower aerodynamic efficiency. It is possible to design two-bladed turbines with similar aerodynamic performance to an equivalent three-bladed design, by increasing the solidity of the rotor; however, this would negate many of the perceived benefits of the two-bladed design /15/. Instead, it would be expected that energy yield would be reduced, versus a three-bladed design, and in theory compensated by a reduction in the CapEx of the machine. /15/ shows that energy yield would be reduced by between 1% and 6%, depending on the design choices for the two-bladed turbine, with a reduction in Load Factor of approximately 0.5 to 3 percentage points.

Two-bladed turbines may also yield a lower cost of energy than three-bladed devices; /15/ suggests this, although highlights that uncertainty remains around particular design attributes for two-bladed devices, such as the teeter hinge (see above). A risk premium would also be expected, as two-bladed turbines would be effectively competing against the incumbent three-bladed design and, whereas a number of the other technologies identified in this report could be implemented as a small part of a system, the selection of a different turbine architecture would represent a significant change in the context of a complete wind farm.

It is also noted that the most likely two-bladed turbine to achieve commercial deployment, the 2-B Energy device, features a notably higher power density than many of its three-bladed competitors, and hence would be expected to yield a lower load factor as a result.

The developers of two-bladed turbines suggest that the two-bladed concept, if "parked" in a horizontal configuration, facilitates helicopter operations and hence increases availability and therefore load factor. However, this increase may be less significant when compared with the performance of modern Service Operations Vessel (SOV)-based O&M strategies (see Section 7).

Although two-bladed designs offer some technical advantages, there are also technical challenges that would need to be resolved via development effort, whilst conventional three-bladed designs will continue to evolve. Due to the deployment success and incumbency of three-bladed turbine designs, it is considered unlikely that two-bladed turbines will be widely commercially deployed in the timeframe considered in this report (to 2035).

5.3 Turbine performance improvements

5.3.1 Introduction to the technology

Offshore wind turbine power curves have been improving due to new hardware and software being developed and deployed on both operational wind farms and new projects. The improvement in wind turbine power curves have been seen due to improvements in wind turbine blade aerodynamics, aerodynamic add-ons to wind turbine blades and improvements in wind turbine components and turbine control software. The introduction of these improvements enables a wind turbine to generate more power for a given wind speed, and therefore to increase Load Factors.

5.3.2 Current technology development status

5.3.2.1 Blade design and aerodynamics

New wind turbine blade designs are being developed and tested by research and innovation projects. These new blade designs have the potential to increase the power performance of offshore wind turbines through improvements in the aerodynamic performance and reduce the costs through the reduction in both blade mass and loading transferred to the nacelle of the wind turbines. An example of new blade profiles developed as part of the Innovative wind conversion systems (10-20MW) for offshore applications research project is shown below.

5.3.2.2 Aerodynamic add-ons

Wind turbine blade aerodynamic add-ons, such as serrated edges and vortex generators, are being deployed on offshore wind turbines to improve the power performance. These add-ons can be applied to both operation and new offshore wind farm projects to improve Load Factor.

5.3.2.3 Blade tip extensions

Several research projects have been developing and testing wind turbine blade tip extensions, similar to wingtips on aircraft wings, to increase the power performance of wind turbines. This technology can be deployed on operational projects to deliver an improvement in Load Factor.

5.3.2.4 Wind turbine drivetrain

Although wind turbine drivetrain failures are not the most common failures on wind turbines, the downtime associated with any failure is always significant owing to heavy lifting equipment required to replace parts. Development of improved reliability, but also design for maintainability, is subject to significant current research and development effort. Recent activity in this area includes:

- Research into plain bearings for use in gearboxes (no rolling elements);
- Development of pseudo direct drive generators (using a contactless magnetic gearbox to scale up the rotor speed);
- Development of on-board crane systems that can remove large drivetrain components without the need for external cranes;
- Increased use of measured data from the drivetrain to predict failures and to inform maintenance plans in advance of failures rather than in response to failure.

As wind turbines scale up, rotor bearings become especially challenging. In direct drive wind turbines, these are integrated in the generator; in geared wind turbines, these are normally used to support the main shaft (between rotor and gearbox). Unlike large diameter pitch and yaw bearings (slew bearings) which can be induction hardened using a process that travels round the forged bearing ring, rotor bearings are case hardened using an oven and as their diameter gets ever larger, constraints on the size of case hardening facilities can be an issue; however, the supply chain is adapting to keep up with the developments.

5.3.2.5 Wind turbine control software

Wind turbines have a closed loop control system at the heart of which is the wind turbine controller containing the control algorithm (control software). This closed loop control system is responding to inputs from the turbine and the range of measurements being taken and feeding into the controller is ever increasing. The controller is acting on this incoming data to control the turbine accordingly via blade pitch control, torque demand and yaw control. Advanced control technology is enabling turbines to be scaled up in size yet to beat the cubic scaling law for mass, i.e. more energy capture and mitigating the penalty of the increased loads from a larger rotor.

Onshore, the majority of utility scale wind turbines control the blade pitch angle collectively (all blades pitching the same), however offshore and with some very large onshore wind turbines, the use of individual pitch control (IPC) is becoming widespread with the associated advanced control algorithms that accompany such pitch control strategies. The use of IPC has the potential to reduce torsional loads on the support structure (which for jackets results in mass savings); clear illustration of the impact of advanced control technology. It is also important to note the impact on the pitch system of this advanced control technology as increased pitch activity places greater demands on pitch bearings and actuators.

Research into nacelle- and spinner-mounted LiDAR (Light Detection and Ranging) is ongoing; the objective of LiDAR is to measure the approaching wind field and feed this data to the wind turbine controller which through the use of advanced control software enables the turbine to pitch accordingly. From the research conducted in this area, it is clear that the main benefit of the use of LiDAR is for reduction of fatigue thrust loads (which represents notable savings in support structures), or enables a larger rotor for the same loads (increased Load Factor). LiDAR systems are commonly sold on their ability to increase energy capture as a retrofit to the wind turbine (and Load Factor), however the potential in this area may be marginal. LiDAR technology still requires more development onshore.

Developments in advanced control technology have the potential to increase the power performance, boosting the performance for wind turbines for a period when loading is low, providing an improvement in the power curve and Load Factor. One example of this technology of the wind turbine control software developed by Siemens Gamesa is the power boost function; this function increases the power performance of the wind turbine under certain operating conditions (for example low turbulence) through a temporary increase in maximum power of the wind turbine generator when the loads and operational temperatures are within the set parameters of the wind turbine.

Wind turbine control software technology can be applied to both operational projects and new projects, and has the potential to deliver an increase in Load Factor by improving turbine performance. Such improvements have been modelled to yield an increase in energy production of approximately 1-2% for a typical UK offshore wind farm, which translates to an increase in Load Factor of a similar proportion. Such upgrades may be costed based on the expected increase in production, such that there is a net reduction in the cost of energy albeit of a smaller proportion than the increase in energy produced.

5.3.3 Impact of the technology

The development of wind turbine performance technology will continue to increase Load Factors and reduce costs. The range of technologies discussed in this section are at varying stages of research and development, and could be deployed on both operational and new offshore wind farms.

It is expected that the performance improvement technologies will become part of standard offshore wind turbines, with each development offering a small incremental improvement in Load Factor. Whilst existing blades already achieve high efficiencies, some improvements are expected; for example, future blades are likely to become more aerodynamically efficient, through the use of alternative blade designs as well as aerodynamic devices and add-ons. It should also be noted that practical constraints may restrict the extent to which significant changes to blade design are developed, for example the transportation implications of large tip extensions.

Advanced control strategies, as with aerodynamic performance improvements, would yield improvements in Load Factor by increasing energy production; advanced drivetrain designs may also offer some efficiency gains but, as drivetrain efficiency is already very high, Load Factor increases would be expected to arise from the improved reliability and hence increased turbine availability (see Section 7).

"Smart" technologies on blades will feature in future offshore turbine designs, mitigating some of the challenges associated with very large turbines. For example, the flexibility of very long blades (even with the use of advanced materials to reduce blade mass and increase stiffness) presents challenges during pitching, which may be mitigated through the use of aerodynamic devices or innovative structural design. However, whilst turbine performance would be improved, the direct impact on Load Factor would be minimal.

Some of the technologies listed in this section would be theoretically feasible for retrofit: aerodynamic add-ons and blade tip extensions could be added to blades in service, and modifications to control software are relatively simple to implement. However, the practical challenges and costs associated with offshore working mean that retrofit is considered unlikely; a retrofit campaign would require the removal of each blade and the use of specialist vessels, and hence significant downtime for what would be expected to be a marginal benefit. The more integrated technologies, such as drivetrain technologies, would not be suitable for retrofit.

As with many of the technological developments detailed in this report, the deployment of these technologies will be dependent on the relative weighting between the costs and risks of the technology versus the improvement in performance and reliability. Each of the technologies described in this section would be expected to yield small increases in Load Factor, largely due to the existing high efficiencies of equivalent current technologies; however, the technologies described in Section 5.3 are also some of the technologies which are more likely to achieve commercial deployment, and the cumulative impact on Load Factor would be expected to be an increase of around 1-2%.

5.4 Alternative turbine technologies

Whilst the three-bladed, upwind, pitch-regulated, variable-speed wind turbine concept is dominant, a number of other technologies are being pursued. For the purposes of this study, the following three categories will be considered:

- Airborne systems;
- Multi-rotor systems;
- Vertical axis systems.

It should be noted that detailed studies of the technologies considered in this section have not been undertaken, in order to fully assess their commercial viability. Due to their developmental status, there is considerable uncertainty on the performance of these systems, and until more information is available regarding design and engineering it is therefore difficult to assess potential costs and Load Factors. A general commentary is included below, based on basic engineering principles and taking into account evidence from previous studies into similar systems. The start-up companies developing some of the technologies in this section claim increased energy production and/or lower costs compared to conventional wind turbines, but it is inappropriate to reference unvalidated claims.

5.4.1 Airborne systems

As observed by Jamieson /15/, many airborne turbine concepts have been patented over the last decade, including some that have connections with high-profile companies e.g. Google funding of Makani /17/. The fundamental attraction of airborne systems is their potential to access superior wind resource at higher altitudes. Airborne systems can be further sub-classified as:

- Systems supported by buoyancy e.g. Altaeros /18/
- Tethered auto gyros e.g. Sky Windpower /19/
- Kites e.g. Makani, KPS /20/

5.4.1.1 Current technology development status

All of the airborne systems listed have achieved some form or prototype deployment which has demonstrated technical feasibility. None of the technologies have reached full scale deployment or demonstrated significant operational longevity.

Airborne systems are currently the preserve of start-ups with little engagement (beyond seed funding) from industrial players with any significant involvement in offshore wind.

5.4.1.2 Impact of the technology

Key technical issues that are yet to be fully resolved for airborne systems include:

- Controllability of trajectories at the end of long tethers;
- Maintaining systems in flight for long periods;
- Reliable power transmission to land through flexible cables embedded in tethers.

Given the current lack of significant involvement of offshore wind stakeholders, it is unlikely that these issues will be solved within the timeframe of this study. The impact of airborne systems will therefore be low, and widespread commercial deployment is not expected within the timeframe of this study.

5.4.2 Multi-rotor systems

The history of multi-rotor wind turbines is long, stemming from designs by Herman Honnef in the 1930s.

The initial motivation for multi-rotor systems was the large-scale deployment of wind power at a time when the only practical structural material for rotor blades was steel, which made the design of large-capacity single turbines impossible due to the enormous weight of large-scale steel blades. In the last 30-40 years, the use of high strength-to-weight ratio composite materials in modern wind turbine blades has allowed very large single rotors to be realised.

Many large scale multi-rotor concepts, including offshore floating systems, were proposed by Bill Heronemus in the 1970s.

However, mainstream wind turbine design has largely ignored multi-rotor systems, perceiving them to bring unnecessary complexity over the upscaling of single rotor systems.

The primary benefit of multi-rotor systems is in the potential to reduce mass (and therefore cost) by side-stepping the square-cube relationship associated with upscaling a single-rotor turbine. When using a multi-rotor system, the total mass of the energy-extracting system is proportional to n, rather than the cube of the rotor radius. This means that, for a given capacity, the ratio of the total mass of the energy-extracting elements of a multi-rotor system to that of a conventional single rotor is $1/\sqrt{n}$. Potential secondary benefits of multi-rotor systems include free yaw stability, increased availability/load factor (if one turbine shuts down due to a fault the remainder of the turbines can continue to operate), and standardisation with subsequent economies of scale of individual turbine units.

5.4.2.1 Current technology status

The multi-rotor concept made a potentially significant move towards the mainstream in 2016 when Vestas /21/ began testing a 900kW four-rotor system built using a combination of new support structure and refurbished 225kW turbines (1980s technology). The impact that this test programme will have on Vestas' longer term technology plans remains uncertain.

Another more disruptive concept has been unveiled more recently /22/ but this is at a very early stage of development.

5.4.2.2 Impact of the technology

Given the current limited interest in multi-rotor systems, it is unlikely that the offshore wind industry will see significant deployment of multi-rotor systems within the timeframe of this study. The impact of multi-rotor systems will therefore be low, and widespread commercial deployment is not expected within the timeframe of this study.

5.4.3 Vertical axis systems

When considering the development of modern wind energy technology, the deployment of vertical axis wind turbines (VAWTs) peaked in the late 1980s. However, new designs or variations on old designs continue to be promoted.

Whilst proponents of VAWTs suggest a number of potential benefits associated with simplicity in the design, for example that there is no need for yaw drive; that the drive train can be mounted at ground level; the lack of pitch systems etc., Jamieson /25/ discusses two fundamental areas where the VAWT performance is significantly compromised when compared to a HAWT: the relatively low rotational speed at which optimum aerodynamic performance is achieved, and the inferior peak performance (at best 10% below that achievable by a HAWT). In combination, these two factors lead to VAWTs being relatively low speed and high torque devices, which therefore have more expensive drivetrains than an equivalent HAWT. Whilst some of this discrepancy in peak performance may be addressed by including active blade pitching, the added complexity that this brings is in direct conflict with the potential benefits associated with simplicity.

5.4.3.1 Current technology status

As mentioned above, VAWT deployments peaked in the late 1980s; little significant development of the technology has been undertaken since the early 1990s although some small-scale turbines are available commercially.

As for the other technologies discussed in this section, there is currently no significant engagement of offshore wind industry stakeholders in the development of VAWT systems. Those promoting the technology are most commonly start-ups or academic groups.

5.4.3.2 Impact of the technology

As discussed above, VAWT systems have significantly inferior performance when compared to HAWTs, and no significant development has occurred in VAWT technology for more than 20 years. In the intervening period, HAWT technology has developed significantly. Given that there is currently no significant engagement from the offshore wind industry with VAWT technology, it seems very unlikely that significant progress will be made within the timescale of this study. The impact of VAWT technology will therefore be low.

5.5 Asian offshore wind turbines

5.5.1 Introduction to the technology

A number of onshore wind turbine manufacturers located in Asia are developing offshore wind turbines for the local market. The offshore wind turbine technology is currently at the early stage of commercial deployment on a number of projects. This offshore wind turbine technology has been developed from onshore models, and are typically designed for lower wind speed sites than located in UK waters due to differences in wind resource in the Asia region. The current wind turbine technology is in the 2-4MW range, which is smaller in both rated capacity and rotor diameter, compared to the current wind turbine technology being installed on UK projects.

The offshore wind turbines being developed by Asian OEMs are similar in configuration and technology to those produced by European manufacturers: three-bladed, upwind turbines utilising either geared or direct drive transmissions, mounted on tubular steel towers. These turbines may also include protection against typhoons, although this has little relevance to their use in the UK or impact on load factor.

Future offshore wind turbine technology located in Asia could be developed for UK offshore wind farms and this technology has the potential to impact both Load Factors and levelised cost of energy.

5.5.2 Current technology development status

The current offshore wind turbine technology in Asia is at the early stage of commercial deployment for 2-4MW offshore wind turbines. This turbine technology is smaller in both rated capacity and rotor diameter than the current 4-8MW wind turbine technology on current operation UK projects.

Wind turbines in Asia are typically designed for IEC Class 2 mean wind conditions, which are lower wind speed projects. For the UK market, new turbine models would need to be developed for Class 1 mean wind condition sites due to UK offshore average wind speeds. A number of wind turbine manufacturers in Asia are developing 4-8 MW Class 1 wind turbines which could be utilised on UK offshore wind farms.

When a turbine manufacturer has proven its turbine technology, this could be deployed on future UK offshore wind farms. This technology has the potential to reduced levelised cost of energy, through reduced turbine CapEx. The impact of the technology on load factor is less clear; this will depend on the power density of future turbines from manufacturers located in Asia, and depending on manufacturer choice the technology could result in increased or decreased Load Factor. Whilst current turbines from Asian OEMs are designed for IEC Class 2 conditions and hence have lower power density, it would be expected that if these manufacturers were to offer a Class 1 turbine suitable for UK site conditions, the power density of the design would be similar to those from European turbine suppliers and hence the inherent turbine performance would also be similar.

5.5.3 Impact of the technology

As the offshore experience and capability of wind turbine manufactures grow in Asia, it would be expected that the performance and reliability of the wind turbine technology will be comparable to the current leading offshore wind turbine technology available in Europe. The rate of adoption of this turbine technology will depend on when the technology reaches a proven status and the costs of the turbine technology compared to existing offshore wind turbine technology.

The wind turbine is the most expensive component of the construction costs for an offshore wind farm and therefore deployment of turbines from Asian OEMs on UK projects would be expected to impact future UK offshore wind farms. It is currently envisaged that the technology will result in a reduction of levelised cost of energy, and an increase or decrease in Load Factors; a slightly decrease in Load Factor is considered more likely as turbine configuration is likely to be similar to European practice and developers would optimise overall project economics rather than maximising Load Factor, whereby reduced technical availability would reduce project LF.

6 IDENTIFICATION OF FUTURE WIND FARM TECHNOLOGY

The following section describes technologies related to the overall offshore wind farm, including balance of plant such as support structures and electrical infrastructure, as well as control systems and wind farm design. Advances in these areas are expected over the period of study, and may contribute to improvements in both Load Factor and cost of energy.

6.1 Floating wind turbine support structure

6.1.1 Introduction to the technology

Floating wind technology offers the potential for the offshore wind industry to bringing previously inaccessible waters within reach, and for allowing site selection on the basis of optimum wind speed as opposed to depth of water, as floating wind can be deployed in waters several hundred metres deep. The floating wind industry is still young, with the first floating wind farm installed in Scotland at the end of 2017, and a handful of concept demonstration projects planned or installed. However, developments are occuring rapidly and new actors, many from the oil and gas (O&G) industry, are now entering the market.

Floating wind technology is leveraging experience gained from both the bottom-fixed offshore wind and O&G industries. Although much innovation and technology development still takes place, four substructure philosophies, all well-known from O&G, dominate the nascent floating wind industry today:

- Spar buoy;
- Tension leg platform (TLP);
- Semi-submersible;
- Barge.

These are categorized based on how the support structures achieve static stability. Support structures for floating wind may either be compliant or restrained for some of the global modes of motions: surge, sway, heave, roll, pitch and yaw. Restrained modes will not imply a total fixation, but displacements in the order of centimetres (e.g. elastic stretch of a TLP tendon) will occur, compared to displacements in the order of metres for a compliant mode. The TLP is typically a restrained structure whereas the spar buoy, barge and semisubmersible typically are compliant structures. Figure 6-1 below illustrates the three of the four main substructure philosophies.

Figure 6-1 Illustration of key floating wind philosophies

6.1.2 Current technology development status

A handful of demonstration and pilot projects (including the first pilot farm) are currently installed worldwide, accounting for a total generation capacity of around 50 MW installed capacity. The two most advanced developments are Equinor’s Hywind spar buoy and Principle Power’s Windfloat semi-submersible. Hywind was the first full scale demonstration, deployed in 2009 and used in the first pilot wind farm with 5 floating units, off the coast of Scotland in 2017. Windfloat, the first full scale semi-submersible prototype, was deployed in 2011. Both these demonstration projects utilized turbines with ratings corresponding to commercial developments at the time. No full scale TLP has yet been deployed although several designs are under detailed development and have undergone scale testing.

Developments are today taking place in Japan, Europe and US. A brief description of selected key developments is provided below:

Concept	Development plans
Hywind	**Technology:** The Hywind system consists of an upwind turbine and tower mounted on a floating substructure and tower. The structure is moored to the seabed with 3 catenary lines which are attached to the structure below the waterline. **Development:** *Hywind Demo:* First full-scale floating unit deployed with a 2MW wind turbine. During autumn 2009, Statoil's Hywind Demo officially started production of electricity and achieved a load factor over 50% in 2011 /27/. *Hywind Scotland:* Five units, each with a 6MW Siemens turbine, were installed in 2017. The wind farm achieved a load factor of 65% during its first three months of operation (November 2017, December 2017, January 2018).
WindFloat	**Technology:** The concept is a semi-submersible, three column floater with a single turbine on one of the columns. An active ballast system transfers water between the columns to keep the platform upright. The mooring system comprise of 3 catenary lines. **Development:** *WindFloat demo:* The WindFloat Demo is developed by Principle Power, and was in 2011 installed equipped with a Vestas V80 turbine of 2MW. The prototype is installed 5km off the Portuguese coast. *Future plans:* Windfloat Atlantic pilot park, consisting of 3 floating units, is currently under development
IDEOL	**Technology:** The floating concrete structure is a ring-shaped platform. The substructure does not require active ballasting, and can be built in both steel and concrete. Sloshing water in the "Damping Pool" is said to counteract swell-induced oscillation. **Development:** The Floatgen project, carrying a 2MW turbine, was inaugurated in October 2017. The project is currently awaiting a weather window for final deployment offshore.
SBM	**Technology:** The concept is a tetrahedral type structure with tension legs at the corners. There are four buoyancy structures: the central column and buoyancy cans at each corner of the structure. **Development:** SBM started the development of the concept in 2015, and was in 2017 selected by EDF Energies Nouvelles to provide the floating wind concept for a pilot project of 3 turbines of 8MW to be installed in the Mediterranean Sea.

In addition to the above-mentioned key technologies which are of technology readiness level above 3, there are technologies in the floating wind industry of lower maturity.

6.1.3 Impact of the technology

Floating wind technology offers the potential for the offshore wind sector to reach previously inaccessible regions and hence allow site selection on the basis of optimum wind speed rather than water depth, which can induce high load factors.

The floating wind technology is however relatively new, with few installed units compared to the bottom-fixed wind industry. There is therefore less data regarding project load factors, and trends for the development of these load factors. The initial results from the Hywind Scotland project exhibited a load factor of 65% during the first three months of operation, although this should be viewed in combination with the high-wind period of operation in the North Sea during November, December and January. In addition, the load factor level is comparable to that of the Dudgeon project, which uses the same turbine, located off the UK east coast during the same time period.

The UK is well-suited to offshore wind, with good wind resource and large areas of relatively shallow water in the North and Irish Seas. As a result, bottom-fixed offshore wind is widely technically feasible, and there is less motivation to develop and deploy floating offshore wind than in other locations with much deeper water. Floating offshore wind may open up the deeper areas of the UK marine estate, such as the northern part of the North Sea and the Atlantic coast of Scotland, where wind resource is excellent but the site conditions are challenging. Deployment in areas of very high wind resource would yield increased Load Factors; a site with an average wind speed of 10.5m/s, such as those off western Scotland, would yield a Load Factor of approximately three percentage points higher than that of a typical North Sea bottom-fixed wind farm with an average wind speed of 10m/s. Project availability would be expected to be lower for the floating wind farm than for bottom-fixed projects in the UK, due to the location of the former in locations with more onerous metocean conditions. Floating offshore wind foundations are large, heavy and hence costly structures, and require significant construction infrastructure; current semi-submersible floating wind foundations comprise more than 2,000 tonnes of primary steel, in comparison with typically less than 1,000 tonnes for bottom-fixed monopile and jacket foundations. The increased cost is expected to outweigh the potential increased energy yield such that the cost of energy from floating wind would be higher than that from an equivalent bottom-fixed project; whilst the floating wind foundation developers will continue to improve and optimise their products, the floating wind industry is also chasing a moving target in terms of the cost reduction achieved by the bottom-fixed projects, and it is expected that, in areas such as the UK with significant areas of shallow seas suitable for bottom-fixed wind, floating wind will continue to be more expensive.

It is noted that major replacements may have a higher impact on floating wind than bottom-fixed, which will be shown from the demonstrator projects. Where major replacements can be performed with jack-up vessels for bottom-fixed offshore wind and the main impact on project availability is related to the accessibility of the vessel, current floating wind technologies often require that the unit is towed to shore for major replacement operations. However, the technologies will be developed with time, and it is expected that floating wind projects will be able to efficiently undertake major replacement operations offshore. Also, it is noted that this could be an advantage for floating wind farms, with an option to tow back to shore using ordinary towing vessels, to perform major replacements, rather than being dependent on jack-up vessels.

6.2 Wind farm control

This section deals with active control of wind turbine wakes, which is currently a very active area of research and development.

Note that the term 'wind farm control' can also be taken to include the electrical control of reactive power, voltage, harmonics etc. but this is largely a separate issue, not closely coupled with wake effects and active power control.

6.2.1 Introduction to the technology

An operating turbine produces a wake in which the wind speed is reduced and turbulence is increased. A downstream turbine on which it impinges will generate less power and experience higher fatigue loading. Wake effects within a wind farm can therefore have a major impact by reducing overall energy production and increasing turbine fatigue loads. Therefore, there has been much interest in recent years in the concept of minimising wake effects through wind farm control. Instead of allowing each turbine to behave 'selfishly' as designed, i.e. to achieve the best combination of energy production and loading for itself, the concept is that an over-arching controller at wind farm level commands changes to the operation of the individual turbines in order to achieve the optimum performance for the wind farm as a whole. This will mean that in any particular condition, the performance of some turbines will be sacrificed to improve the performance of others, such that the overall performance of the wind farm is optimised.

This optimisation may be defined simply in terms of maximising energy production, or it may also include reduction of turbine fatigue loads: this may help to reduce operation and maintenance costs over time, and it may allow the productive life of the wind farm to be extended. At the wind farm design stage, the reduction in wake-induced fatigue may even permit closer turbine spacings, or allow the use of lighter and cheaper turbine components, such as blades, or support structures than would otherwise be needed; however, any blade weight reduction would be slight, due to blade design requirements.

Two different strategies can be used to help minimise wake effects:

1. **Induction control**. An individual turbine's wake is weakened by reducing the power produced by the turbine. The wake will then have a less detrimental effect on any downwind turbines on which it impinges.
2. **Wake steering**. By introducing a deliberate yaw misalignment, momentum conservation dictates that a turbine's wake will be pushed sideways, and thus can be 'steered' away from downstream turbines. This can reduce or avoid the detrimental effect of the wake on those turbines.

In the general case, there is no reason not to use both strategies in combination as this should allow a more optimal solution. For each wind condition, the wind farm controller would choose the best combination of power reduction and yaw misalignment set-points to use for each turbine.

6.2.2 Current technology development status

Wind farm control may be implemented through different strategies, which vary in complexity and technological development, as follows:

1. Traditional sector management: A simple approach, which has been used for many years on some wind farms where wake effects are sometimes problematic, is to switch off some turbines when they are heavily wake-affected (for example every other turbine along a closely-spaced row) in order to prevent excessive fatigue loading or vibration. Clearly this results in a significant loss of energy production, and is unlikely to be an optimal solution. Nevertheless, an

understanding of the wake interactions can be used to pre-determine the best combination of turbines to switch off in any given wind condition.

2. Quasi-static open-loop feedforward control: This is a relatively straightforward concept in which a database of optimal set-points for all the turbines (for induction control, wake steering or both together) is pre-calculated for a matrix of different wind conditions by optimising for each wind condition against a chosen merit function. Then, during operation, given the wind condition at any time, the set-points for each turbine are obtained by interpolation from this database. As a minimum, the wind condition should be defined in terms of wind speed, wind direction and turbulence intensity.

   Such a control scheme is also referred to as an 'advanced sector management' strategy. It may be expected to be effective as long as the wind conditions are relatively slowly-varying.

   The technology is still at an early stage of development. There have been one or two limited field experiments, and the first full field tests of such a concept are currently being planned.

3. Dynamic closed-loop feedback control: At the more complex end of the spectrum, a dynamic closed-loop controller attempts to use detailed measurements across the wind farm to keep track of the wakes and wind flows in real time, and use this information to make rapid adjustments to individual turbine set-points, for example by using a model-based predictive control scheme. High-definition measurement feedback gives the potential for much more dynamic response which should be less sensitive to inaccuracies in the underlying models. Such schemes are still speculative, very much at the research stage, and not yet ready for commercial deployment.

Wind farm control has the potential to increase revenue and reduce costs for wind farm owners and operators. However, to realise these benefits, cooperation is needed also with turbine manufacturers, since the wind farm control causes changes to the operation of the individual turbines. The turbine controllers may need to be adapted to respond to the power reduction and yaw set-points sent out by the wind farm controller, and so that operation away from the normal operating envelope does not cause errors to be flagged; and the loading implications need to be considered to ensure that the design of turbines is not compromised.

Grid operators may also have an interest in wind farm control. Any curtailment demands may be met more precisely if managed by a controller at wind farm level which takes account of wake effects. For the wind farm owner or operator, a wind farm controller can be designed to achieve a given level of curtailment while managing fatigue loads across the turbines in as beneficial a way as possible. Also, adjustment of total wind farm active power can be used to help mitigate financial losses from forecasting errors. Control of total wind farm active power on a timescale in the order of 0.1 – 10 seconds can also be used to mitigate grid frequency variations, using the turbine rotor kinetic energy as a short-term energy store. This may be of value to the grid operator.

6.2.3 Impact of the technology

There is much current interest in the possibilities of wind farm control, especially if total wind farm power output can be increased. Any increase in power output is the result of a balance between increases on some turbines and decreases on others, and is therefore likely to be fairly small – maybe of the order of 1% or so – and very sensitive to the accuracy with which the effect on each turbine can be predicted. Current models used to predict these effects are validated only up to a point, and not necessarily for the wide range of different combinations of atmospheric conditions which any given wind farm may encounter. A process of field tests and measurements, iterating with improvement and validation of the models used to design the controllers, is essential for building confidence in the usefulness of this technology. The measurements required to detect such marginal effects with confidence are quite challenging in themselves.

However, even potential increases in energy production of the order of 1% may be very valuable, so the goal is worth pursuing.

Reduction of fatigue loading may be less sensitive and hence easier to achieve with confidence. However, the economic benefits of reduced fatigue loading are much more difficult to quantify and are subject to future uncertainties, whereas increased energy production today has a more definite and quantifiable benefit. Fortunately, it appears likely that wind farm control can achieve increased energy production and reduced loads at the same time – it need not be a choice between one and the other.

For any wind farm, the usefulness of wind farm control depends crucially on the wind turbine spacing and layout, as well as the wind conditions: not only the wind rose but also the range of turbulence intensities.

6.3 Layout design

6.3.1 Introduction to the technology

Offshore wind farms have significantly grown in size as the industry has developed and matured, with projects currently in pre-construction consisting of over 150 wind turbines and with installed capacities in excess of 900MW. This growth in project size has the potential to reduce Load Factors, as wake effects are more significant in larger projects and therefore large projects exhibit reduced array efficiency.

Offshore wind farm developers typically optimise the wind farm configuration, including the wind turbine layout density and wind turbine locations, to reduce wake effects and increase wind farm Load Factor.

6.3.2 Current technology development status

The installed capacity and configuration of offshore wind farms has increased as technology develops.

This growth in size of offshore wind farms has the potential to impact Load Factors due to wake effects. Wind turbines extract energy from the wind and downstream there is a wake from the wind turbine, where wind speed is reduced. The wake effect is the aggregated influence on the energy production of the wind farm, which results from the changes in wind speed caused by the impact of the turbines on each other. The wake impact reduces the Load Factor for offshore wind farms and is dependent on the size of the wind farm, the number of wind turbines and wind turbine layout design.

The optimisation process to reduce wake losses in projects has resulted in a decrease in the density of offshore wind farms, with a reduction in both the number of turbines and wind farm capacity per square kilometre.

Furthermore, the use of larger wind turbines is usually accompanied by increased spacing between turbines; whilst the larger turbines produce larger, longer-lasting wakes, the increased spacing may reduce wake effects by enabling wakes to dissipate before reaching the next downstream turbine. The balance of these effects is complex, and dependent on specific parameters such as the wind regime and project layout; overall, it may be expected that a project comprising fewer, larger, more widely-spaced turbines would exhibit greater wake efficiency (and hence greater Load Factors) than an equivalent project comprising more, smaller, more tightly-spaced turbines. New methods of optimisation of the wind turbine layout, to reduce the wake impact, are being developed by the offshore wind industry. Examples of four potential layouts considered for one offshore wind farm are shown below /28/, showing the extent to which layout is considered in wind farm design and how layouts may be adjusted to maximise energy production.

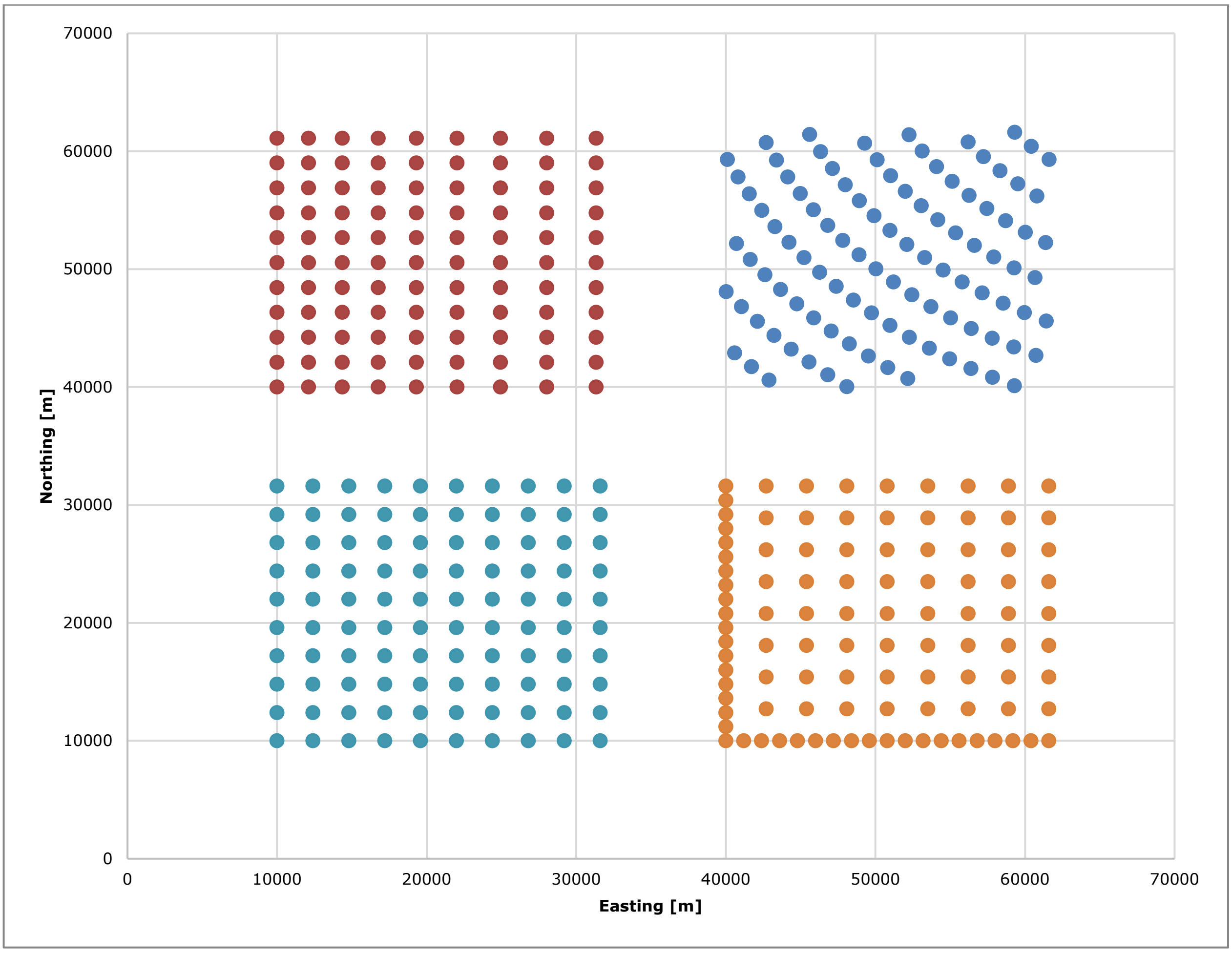

Figure 6-2 Examples of four potential layouts designed considered for one offshore wind farm /28/

6.3.3 Impact of the technology

It is expected that trends of increasing installed capacity will continue in developed markets, albeit with a practical upper limit on total project installed capacity related to the length of the construction programme. To reduce the impact of wake effects, alongside larger further-from-shore project areas, it is expected that the installed density of offshore wind farms will reduce, with a reduction in both the number of turbines and wind farm capacity per square kilometre to continue for future projects.

Enabled by advances in both computing power and modelling techniques, optimised layout design is expected to become the default approach in future wind farm development. The benefits of advanced layout design would be seen in increased energy production (noting that a reduction in CapEx, due to reduced loads, may also be possible), which directly influences Load Factor. Modelling suggests that optimised layouts can offer a reduction in cost of energy of approximately 1-2%, with an increase in energy yield of a similar proportion; the net increase in Load Factor would therefore be of the order of up to one percentage point.

6.4 Electrical transmission system

6.4.1 Introduction to the technology

Wind farm electrical transmission systems are the electrical connection of the wind farm from its geographical location to the onshore electricity system. The design of the transmission system will be, in the main, determined by the following criteria:

- Installed capacity;
- Geographical spread of the offshore wind farm;
- Wind turbine terminal voltage;
- Wind turbine grid capability;
- Onshore electricity system locality and voltage level.

In cognisance of the above issues, a number of options are available for the connection of the offshore wind farm to the shore:

- Extended Array Cables;
- Step-Up Transformer Substation(s);
- High Voltage Direct Current substations (this option also requires step-up substations).

These transmission system arrangements are discussed in the following section.

6.4.2 Current technology development status

Electrical transmission systems for offshore wind farms need to be designed therefore to satisfy the requirements of specific projects. For relatively small projects such as the early offshore wind farm developments in the United Kingdom, the transmission systems were relatively simple and were, in effect, extended array cable circuits from shore to the nearest offshore wind turbine.

With larger and more distant offshore wind farms it is necessary to consider other methods of transporting the power to shore. When electricity is transported, electrical losses are incurred. Losses arise from the product of the current (squared) and the resistance of the conductors. If the current can be kept to a minimum, then the losses can also be reduced and less power is lost in the journey to shore. Therefore, it is necessary as wind farms become larger to consider higher voltages for transmission systems. Accordingly, offshore substations become necessary as:

a) A central location to which the output of the wind turbines is brought, and

b) A means of stepping the voltage up, from the array system voltage to the transmission system voltage,

c) Multiple (array system voltage) cables to shore become excessive and costly when compared to the installation of an offshore substation and fewer transmission system cables.

The basic options described above are shown in the figures below.

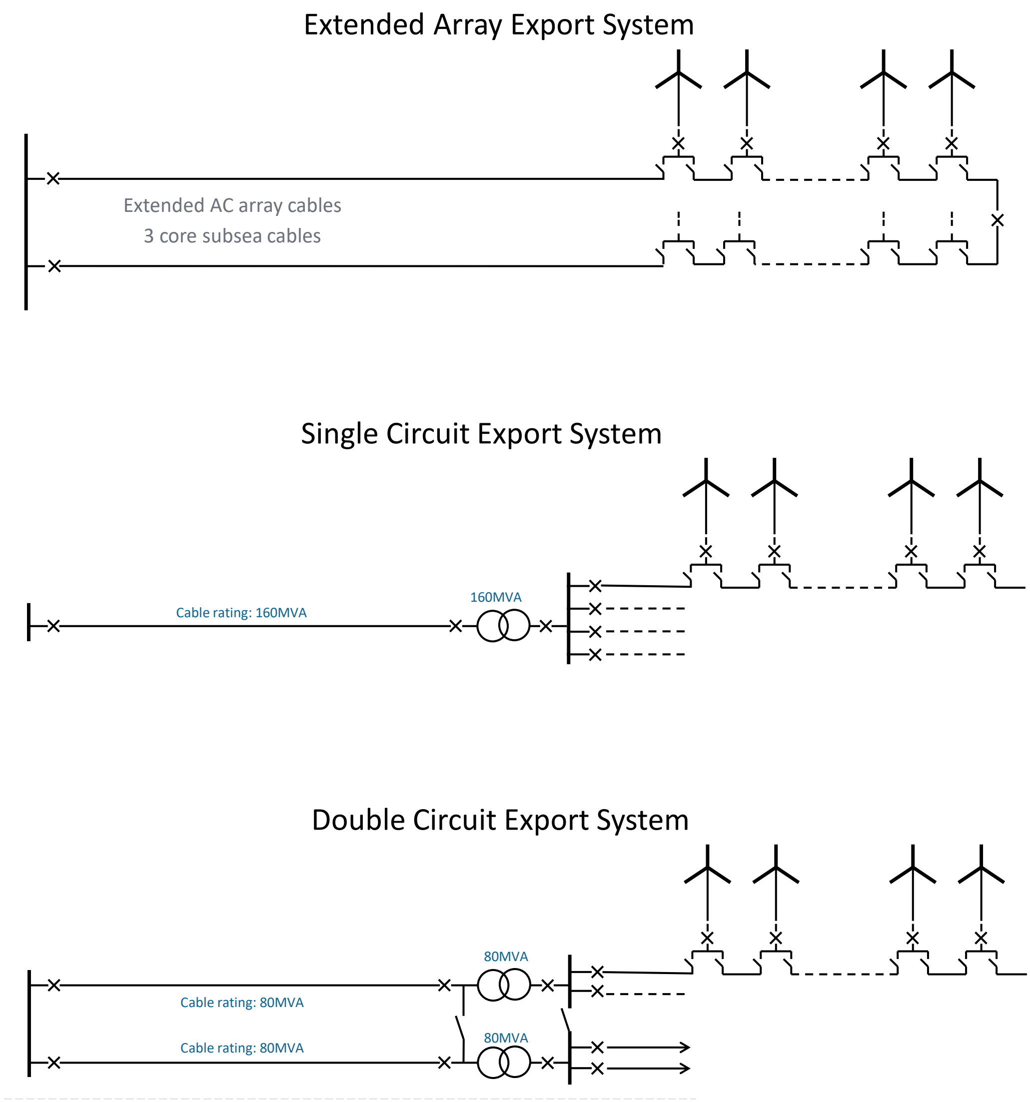

Figure 6-3 Basic options for export of electrical power

When projects and transmission distances become very large, transporting power using Alternating Current (AC) technology becomes technically challenging and ultimately economically and technically unfeasible. Projects off the coast of Germany are of such distance from shore that High Voltage Direct Current (HVDC) technology is necessary, and to date are the only examples of HVDC systems in offshore wind. For distant and large offshore projects off the coast of the United Kingdom, HVDC will become a realistic option.

Other potential options for long-distance transmission are being developed; however, they are presently only at a conceptual level. The transmission connection methods described above are becoming more established and are likely to prevail for many years to come.

6.4.3 Impact of the technology

Due to the high efficiency of electrical transmission systems, improvements in Load Factor relating to the electrical system are likely to be minimal.

The load factors of transmission systems utilising step-up transformers could be improved by increasing the ratings of equipment and therefore reducing the losses. However, the penalty would come as increased capital costs. This approach would also apply to HVDC technology, but similar increases in capital costs.

Another option that may be considered is increasing the level of redundancy in the export system by increasing the number of circuits/systems to the shore. If this approach were taken, power could be directed around an outage on one circuit, and thus export system availability maintained. The offshore wind industry has experienced reduced availability due to export system outages, although this is becoming less frequent in recent projects, and is expected to continue to reduce over time. This approach of increased redundancy is, to varying degrees, already being implemented by developers.

7 IDENTIFICATION OF FUTURE OPERATIONS AND MAINTENANCE TECHNOLOGY

Offshore wind farms are operated and maintained through a variety of different strategies and access methodologies. Such access strategies are predominantly concerned with the transportation of technicians, parts and equipment from an operations and maintenance base and their subsequent safe transfer between a marine vessel and the offshore structures. As the offshore wind industry has developed, new vessel technology and design, access solution systems and consideration of helicopter operations have emerged in the market and have started to prove relevant and beneficial to most projects. A description of the current technology and the most relevant developments in access strategies is given in the following sections.

It should be noted that offshore-specific design of wind turbines takes into account the challenges of offshore operation and access, and hence design-for-maintenance is more important than for onshore machines. In particular, design of components and systems for reduced maintenance helps to reduce the need to access turbines for maintenance, contributing to increased availability and Load Factor; direct drive drivetrains and improved power electronics are examples of this approach.

Wind turbine availability is the dominant factor within wind farm availability; availability of the electrical balance of plant and grid connection is very high (typically in excess of 99%). As Load Factor is a function of wind farm availability (see Glossary), turbine availability therefore influences Load Factor – an increase of one percentage point on turbine availability would result in a similar increase on net energy production, from which Load Factor is calculated.

Revision of the O&M strategy is one of the few technologies detailed in this report for which "retrofit" is possible; indeed, offshore wind farms are already adjusting O&M approaches based on both project learning and improved technologies. These technologies are also either commercially available or very close to achieving this, and hence present opportunities to offshore wind farms to increase availability and Load Factor in the near future. It should be noted that the impact of improved O&M access is very project-dependent, as it depends on factors such as number of turbines, distance from shore and site metocean conditions, and hence quantification of improvement in generic terms is difficult.

The deployment of advanced O&M strategies (assuming the optimum strategy is employed for each individual project) is expected to contribute to the increase in project availability from approximately 93%, which represents a reasonable historical average for UK offshore wind projects, to approximately 96%, which represents current best practice. This value will likely increase further, as advanced O&M strategies become the default approach although, obviously, there are practical limits to the extent of any further increase. The increase in project availability noted above translates to an increase in Load Factor of approximately one to two percentage points. Whilst more capable O&M strategies would be expected to increase OpEx, this is typically outweighed by the increased production such that advanced O&M strategies would be expected to yield a reduction in LCOE of a similar order of magnitude to the increase in Load Factor.

7.1 Onshore-based Service Vessels

7.1.1 Introduction to the technology

Crew Transfer Vessels (CTVs) form an integral part of O&M strategies for currently operational projects. Their purpose is generally to transfer personnel and moderate-sized parts to near-shore projects in support of both scheduled and unscheduled maintenance activities. In some cases, CTVs may also operate from fixed offshore bases or Service Operation Vessels (SOVs), as discussed in Section 7.2.

CTVs are typically designed with large foredecks to allow plenty of space and flexibility for transporting components and equipment. This arrangement also means that all items are located underneath the turbine davit or nacelle crane when the vessel is in position against the boat landing. The maximum size of parts, tools and consumables that may be transported is usually governed more by the lifting capacity of the davit or nacelle crane on the turbines than by the deck capacity of the CTV.

CTVs are typically capable of transferring up to 12 technicians and of achieving speeds of approximately 20 knots. Industry-quoted figures suggest that CTVs may typically be used to transfer technicians to offshore structures in up to ~1.5m Hs; however, operating experience suggests that this is often not achievable, especially for smaller vessels. On the other hand, 'enhanced' and larger CTVs (~18-27m length overall, LOA) with new designs and access solution systems have started to report transfer capabilities in up to 1.75m Hs.

There are a range of Rigid Inflatable Boats (RIBs) and other lightweight vessels currently available for offshore wind farm operations. These vessels are small and designed for light work and as quick response during installation and operation activities offshore. The vessels are typically in the range of 5m to 15m in length, and are capable of achieving speeds of approximately 35 knots, well in excess of those attained by most aluminium catamarans and larger CTVs.

Although these vessels offer greatly reduced transit times, they are unsuitable for personnel transport over large distances and/or in onerous conditions. They may, however, offer advantages over CTVs for some operations, such as when quick fault diagnosis and subsequent turbine restart is possible without the need for substantial spare parts or additional equipment, for use as supplementary transfer vessels when a greater number of service crews are present for a particular maintenance campaign, and for in-field transfers, particularly in sheltered sites in the summer months when conditions are relatively benign. Such vessels may also be utilised as "daughtercraft" in conjunction with SOVs (as described in Section 7.2).

Indicatively, quick response vessels might be capable of transferring technicians onto offshore structures in 0.75m – 1.25m Hs, depending on their size and hull design as well as the profile, frequency, and direction of the waves.

7.1.2 Current technology development status

Since CTVs are the main workforce for current offshore wind projects, the development of these vessels has seen great growth in numbers and vessel designs. For the first offshore wind projects, operations were performed with a mixture of quick response vessels and CTVs. First vessels deployed in the industry ranged between 15m and 18m in length, of a monohull or catamaran design. As experience was gained with these vessels, the limited transfer capabilities became apparent, and therefore larger and more capable vessels were required in order to reduce waiting on weather days.

Current projects and projects in planning have moved into consideration and deployment of larger vessels, typically ranging between 18-27m in length. Larger vessels would typically have higher transfer capabilities (with some exceptions depending on site conditions and the vessel design), therefore with larger vessels more weather windows could be exploited.

Further to these developments, new vessel designs have started to reach the market. New designs have targeted to improve comfort during transit, transit speed and transfer capabilities. Three examples of such vessels are the Windserver (25 and 30m concepts by Fjellstrand), the 26m NautiStrat (by Nauti-craft) and the 18 and 23m Mobimar vessels (by Mobimar). Some of these designs have already been trialled and tested; Windservers are deployed in offshore wind projects. These vessels have increased the transfer capabilities of the project with transfer capabilities of approximately 1.75m. The Mobimar and NautiStrat vessels claim that transfer capabilities could increase to up to 2.5m Hs which, for reference, is the typical transfer capability of current purpose-built Service Operation Vessels (SOVs) as further described in the following sections. It is considered unlikely that these limits would actually be achieved in practice; however, if these vessels are commercialised, it is likely that transfer capabilities and speed would improve and therefore accessibility to offshore windfarms would be improved.

7.1.3 Impact of the technology

New development of CTVs have certainly demonstrated improvements in transfer capabilities. These improvements translate into better accessibility to the project, and therefore a reduction in downtime due to weather delays. Modelling and projects' operational experience show that improvements in transfer capabilities directly translate into improvements of WTG technical availability. An improvement on vessel transfer capabilities from 1.5m Hs to 1.75m Hs could represent an increase of up to 1.5% in WTG technical availability, depending on project conditions such as metocean conditions, distance to port and number of turbines; this increase in availability would translate to an increase in Load Factor of a similar proportion.

7.2 Offshore-based Service Vessels

7.2.1 Introduction to the technology

An alternative to onshore-based strategies has been the deployment of adapted floatels or Offshore Support Vessels (OSVs), and more recently of new purpose-built Service Operation Vessels (SOV). These vessels are considerably larger than traditional CTVs, and are designed to operate in harsh climates and to stay at sea for periods of a week or more; therefore, they are fitted with personnel quarters and facilities. Such vessels are typically upwards of ~50m in length, and have heave-compensation gangways and Dynamic Positioning capabilities to operate in proximity to wind turbines or other offshore structures. Some of the floatels and OSVs available in the market have been mobilised and equipped to the specific needs of offshore wind construction and operations.

Whilst these converted floatels or new built OSVs have full capabilities to operate an offshore wind farm, their use has been mainly limited to support during construction of projects or O&M seasonal campaigns. The recently-developed purpose-built Service Operations Vessels (SOVs) are the vessels with long-term O&M contracts of 5-15 years in different offshore wind farms in Europe. These vessels have become the state-of-the-art, and are specifically developed for the offshore wind industry with OEMs and developers having chartered such vessels to maintain extensive portfolios.

SOVs are large vessels above 50m in length and include heave compensated gangways with a reliable Dynamic Positioning system which, in conjunction, allow the transfer of technicians to the wind turbines or offshore platforms in metocean conditions of up to 2.5m Hs. The vessels are also typically equipped with helidecks and launch and recovery systems for daughter craft. During more benign conditions, these daughter craft can be deployed from the vessels to transfer technicians to the turbines, increasing their versatility. An example of a modern SOV is the Windea La Cour vessel operated by Siemens at the Gemini Offshore Wind Farm, which comprises 150 WTGs, in the Dutch North Sea.

These vessels are designed to stay at sea for extended periods (typically 2-4 weeks) and hence are fitted with personnel living quarters (typically for 40 to 60 passengers) and facilities. This approach fits well with the dispersed nature of offshore wind projects, since multiple crews can be deployed at any given moment, but historically has had limited value to other offshore industries and hence is currently an emerging technology which is being deployed in large and far-from-shore European projects. Furthermore, subject to appropriate risk assessments and mitigation procedures, the combination of such large vessels and the advanced access systems provides the additional possibility of nighttime working, which could provide further improvements in WTG availability as downtime due to waiting on technicians' shifts could be eliminated.

7.2.2 Current technology development status

Given the early status of far-shore wind energy projects, the number of dedicated offshore wind SOVs is currently limited. However, the technology can be considered proven and commercially available, and there are numerous vessels in construction as well as various designs under development, tailored specifically to the needs of offshore wind operators.

7.2.3 Impact of the technology

SOV-based O&M strategies are becoming increasingly common for offshore wind farms, particularly for the largest and furthest-from-shore projects. SOVs offer very high availability, and the high working limits of these vessels contributes to reduced risk of low availability; modelling suggests that SOVs may not be the optimal O&M strategy for smaller projects, but the reduced availability risk appears to be sufficient motivation for the selection of an SOV strategy even in such cases.

The deployment of an offshore-based strategy which includes the deployment of these vessels represents improvements in many aspects of the operations of a wind farm, including:

- Reduced transit times as the vessel stays on site and technicians live in the vessels;
- Improved accessibility to site with Hs transfer limit up to 2.5m;
- Availability of most spare parts on site as the vessel works as the O&M warehouse;
- Potential to work night shifts which could eliminate waiting on shift downtime.

Combined, these enhancements are likely to represent WTG technical availability improvements in the range of 1-3% depending on project conditions such as metocean conditions, distance to port and number of turbines. In turn, improved technical availability would contribute to increased Load Factors of a similar proportionate increase.

It is expected that SOV-based strategies will be increasingly widely used, over both the near term (approximately five years) and longer-term. It is noted that that improved turbine reliability, and/or fewer larger turbines, would reduce the benefit of SOVs over less-comprehensive strategies, but as SOV performance is proven, and the SOV market develops, SOVs will become economically optimal even for smaller projects. Accordingly, with increased use of SOV-based O&M strategies, it is expected that the availability and hence Load Factor of future projects will be higher than historical averages.

7.3 Access Solution Systems

7.3.1 Introduction to the technology

In addition to the standard step-over approach to reach the boat landing ladder and access the turbines, there are a variety of systems for personnel and equipment transfer to a turbine structure which are commercially available or under further development. The Ampelmann and the Uptime gangway systems are the most recognisable and proven solutions in the current time. These, and a range of additional systems which are emerging in the current market, are briefly described below. It is important to note that there are a wide variety of products under development, therefore this list shall not be considered as an exhaustive representation of the market.

7.3.2 Ampelmann and Uptime (motion-compensated gangways)

Ampelmann Operations BV and Uptime International have developed different access systems which are based on an assembly of hydraulic and control systems connected to a gangway platform. The systems are designed to be fixed to the deck of a large vessel (ideally more than 70m LOA). A control system monitors the real-time motion of the platform and the vessel, and uses these measurements to actively compensate for the motion of the vessel, creating a steady base for personnel and equipment transfer. The transfer is then made across the gangway attached to the platform. As the vessel motions are completely compensated the gangways are steady and standing still.

The Ampelmann and the Uptime systems have already been used in support of both installation and O&M activities associated with the offshore wind industry. Examples include assistance during the installation of transition pieces, access during the grouting of monopile structures, and during maintenance of offshore wind farms.

7.3.3 Motion-compensated gangways

Osbit Limited has developed a variety of access systems which include passive and active compensation gangway systems which stabilise the front of the boat in relation to the landing structure. The Maxccess passive and active compensated gangways are similar to the Ampelmann and the Uptime products which require a large vessel for their installation, whilst the smaller platform (the T-series) is designed to be fixed to the deck of a small crew transfer vessel (18-27m length). The system clamps onto one of the tubular spars of the boat landing to create a steadier connection for personnel and equipment transfer.

The T-series platforms is commercially available and has been deployed in few offshore projects such as the Fukushima project, Greater Gabbard and Sheringham Shoal projects.

Otso Limited has developed the Autobrow access system which similar to the Maxccess T-Series, consists of a motion compensation gangway system which stabilise the front of the boat in relation to the landing structure. The Autobrow is designed to be fixed to the deck of a small crew transfer vessel (18-27m length). The gangway connects onto one of the boat landing to create a steadier connection for personnel and equipment transfer whilst the tower end of the gangway is pivoted to allow the up and down movement and roll of the vessel.

The Autobrow platform has completed testing and trials, however no commercial deployment is known at the time of writing.

7.3.4 Tube Docking Device (TDD)

Offshore Transfer Devices has developed the Tube Docking Device (TDD) which consists of a cylindrical fender tube which, enabled by a hydraulic system, clamps onto the boat landing of the wind turbine therefore stabilise the front of the boat in relation to the landing structure. The TDD is designed to be fixed to the front of almost any vessel. The first prototype has completed the concept trials in the first quarter of 2017 at Scroby Sands and was able to hold its pivoting jaws with negligible movement in wave heights up to 2.7m. No commercial deployment is known up to the time of writing this report.

7.3.5 Limpet Offshore Personnel Transfer System

Limpet Technology is currently developing a new access solution, the Limpet Offshore Personnel Transfer System which consists of an active compensation fall arrest system which tracks the vessel movement and regulates the pulling or dropping of a connection line which allows a technician to climb up or climb down the structure ladder in a safer way. The system is installed at the transition piece deck; after being hooked up with the system, the technician can then climb up the ladder. The system has been tested in December 2017 and the developer estimates that transfers using the system could be performed in wave heights up to 3m; however, the system is still under development and no commercial deployment is known at the time of writing.

7.3.6 Current technology development status

From the systems described above, the Ampelmann, the Uptime and the Maxcess systems are fully commercially available and have been already deployed in the offshore wind market in different regions of the world, whilst other products are still under testing and development. It is expected that these products could see further development and reach commercial availability in the next 2-5 years.

7.3.7 Impact of the technology

The systems described in the sections above are considered the most relevant in the market; however, many more concepts are under development which could develop further in the industry. Each has the possibility to increase accessibility to an offshore wind farm from the current typical limit of 1.5m significant wave height using standard catamaran CTVs to up to 2-3m. An improvement on accessibility will directly translate into a reduction of downtime due to weather delays and therefore an improvement of WTG technical availability. For this reason, it is expected that the deployment of such systems could represent improvements in WTG technical availability in the range of 0.5-3% depending on project conditions such as metocean conditions, distance to port and number of turbines.

7.4 Helicopter access

7.4.1 Introduction to the technology

Helicopters have been used for many decades for accessing offshore structures in both civil and military capacities. However, their regular use in the offshore wind sector is still comparatively rare, partly reflecting the relatively early stage of the industry.

The real benefit of accessing offshore turbines via helicopter stems from their inherent insensitivity to wave conditions and the improvement in stability and hoisting capabilities achieved under high wind speeds coupled with the high transit speeds at which they operate. Other meteorological conditions, primarily poor visibility and low cloud base, may restrict operating windows under visual flight rules, but often these occur during relatively benign periods when access can be made by the CTVs anyway. The good accessibility and quick response time offered by helicopters fits well with the relatively high-frequency, low-effort failures which form a large proportion of wind turbine downtime, leaving vessels to attend to the less frequent, larger failures as well as the scheduled maintenance burden.

While project operators are initially met with increased operating costs due to the inclusion of a helicopter, modelling results and recent industry experience indicate that this may be outweighed by the increase in revenue due to reduced downtime as a result of the lower exposure to weather risk and speedier transit.

7.4.2 Current technology development status

For relatively near-shore projects, the dispersed nature of wind farms is well catered for by frequent trips with relatively small aircraft such as the H135 (formerly the Eurocopter EC135) which have a typical capacity of 1 pilot plus 6 to 7 passengers and an approximate cruising speed of 250 km/h. This helicopter model has been deployed in more than 10 offshore wind projects. As projects move farther from land, however, this simple "shuttling" approach with small aircraft becomes less attractive, since increased transit times require larger helicopters with greater endurance and the benefits of rapid response are reduced. For this reason, projects are expected to deploy larger aircraft, and offshore bases to deploy technicians. In some cases (such as for Hornsea Project One) the offshore substations will be supplied with refuelling /29/ systems to allow more time at site and deployment of technicians from the offshore substations to the turbines.

Larger helicopters to be used in future far-shore projects are twin-engined helicopters with larger passenger capacity and increased speed, such as the Airbus H145 and Leonardo AW169.

7.4.3 Impact of the technology

Modelling and industry experience shows that the deployment of helicopter operations will increase accessibility to site and therefore reduce WTG downtime due to waiting on weather, therefore, these is likely to increase WTG technical availability by approximately 1-2% depending on project conditions such as metocean conditions, distance to port and number of turbines.

7.5 Highly-capable Crew Transfer Vessels

7.5.1 Introduction to the technology

As the offshore wind industry has recognised the imoprtance of accessibility, new vessel technology has been developed focused on the improvement of the transfer capabilities and speed of the vessels. The most relevant of these developments are SWATH (Small Water-plane Area Twin Hull) vessels, SWASH (Small Waterplane Area Single Hull) vessels and Surface Effect Ship (SES) vessels.

7.5.2 SWATH and SWASH vessels

SWATH vessels perform turbine transfers in the same manner as CTVs, but due to their hull design are generally more stable than typical monohull or catamaran vessels. SWATH vessels typically range between 20-30m length and are capable to accommodate 12-24 passengers and achieve speeds of up to 25 knots. Their specialist hull design provides the majority of the buoyancy well below the surface, thus minimising the impact of the vertical motion of the waves on the vessel. For this reason, the draft of SWATH vessels tends to be significantly greater than conventional monohull or catamaran vessels. This can cause access difficulties at very shallow sites and harbours and hence may place restrictions on the service base used.

A further development of the SWATH design is the SWASH prototype Explorer. This type of vessel is smaller with a 20m length and uses a single submerged hull with foils front and rear, and two thin section port and starboard as the stabilizing element of the design.

Due to their inherent stability, these vessels allow technicians transfers in up to 2m Hs (with some operators claiming transfers could be performed in up to 4m Hs). These vessels may prove to be cost-effective solutions for wind farms situated in onerous wave climates or relatively far from port, and have been trialled at the Bard Offshore Wind Project in the German Bight.

7.5.3 Surface Effect Ship Vessels

A recent further development into vessel technology is the Fast Crew Transfer Vessel with Surface Effect technology (the Wavecraft CTV vessel). This new vessel technology could provide an alternative to operate an offshore wind project far from shore or with onerous wave conditions. The Wavecraft vessels have an air cushion catamaran design and are equipped with a sophisticated motion control system, which compensates vertical wave motion allowing faster and comfortable transit and safe access to turbines under more onerous conditions with reported transfer limits up to 2m significant wave height and average transit speeds between 30-45 knots. These vessels range between 26-27m length, can transfer 12 or 24 technicians and are deemed to provide significant improvement on accessibility to offshore wind farms as improvements on speed and transfer limitations have been demonstrated on offshore trials.

7.5.4 Current technology development status

SWATH vessels have been trialled and tested in offshore wind projects; however, at the time of writing, these vessels have been mainly used for specific temporary maintenance or repair campaigns and there are no long-term contracts of SWATH or SWASH vessels for daily O&M operations in offshore wind projects. This is likely due to the higher daily rates for such vessels, which make these vessels more costly than conventional CTVs for day to day operations.

The Umoe Mandal Wavecraft vessels have been trialled and tested for 8 months in Sheringham Shoal and are currently being tested by Orsted at the Horns Rev 2 offshore wind farm.

7.5.5 Impact of the technology

Due to the significant improvement on accessibility provided by the SWATH and SWASH type of vessels and based on modelling and industry experience, it is expected that projects which deploy these new types of vessels could see improvements on WTG technical availability between 1-2% whilst projects deploying the Wavecraft SES vessels are expected to show even higher improvements of 1-3% in technical availability due to the additional reduction on transit times that these vessels provide. Any increase in WTG technical availability will manifest as increased Load Factors, of approximately similar proportionate increase.

8 POTENTIAL TO IMPROVE LOAD FACTOR OF OFFSHORE WIND FARMS IN THE UK TO 2035

The offshore wind future technologies identified above were modelled, to show the expected impact on both Load Factor and Cost of Energy of each technology, followed by a survey of personnel from the offshore wind industry to validate the results of the modelling.

This section details the assumptions, results from the modelling, and the results from the industry survey.

8.1 Modelling Assumptions

The following section summarises the modelling assumptions to show the expected impact on both Load Factor and Cost of Energy of each technology.

A series of hypothetical offshore wind farms were modelled (see Section 3.4 for details of the modelling approach) to show the impact of each future technology on Load Factor and cost of energy. A baseline scenario approximates to current offshore wind farm characteristics, based on the most recent UK CfD awards, to which each future technology has then been applied separately. The individual scenarios enable the direct impact of each technology to be quantified; a “combined” scenario was also modelled to present a likely upper bound of future Load Factors, in which the complementary technologies that are expected to achieve commercial readiness by 2035 were applied in combination, showing the cumulative impact of these technologies including inter-dependency and overlap between them.

The modelling is based on some generic assumptions intended to capture representative project characteristics of future UK offshore wind farms, and to yield comparable results between technologies excluding specific manufacturer choices.

8.2 Baseline Assumptions

The modelled scenarios are based on a theoretical project with the following parameters (except where varied, as detailed below):

- 900MW installed capacity;
- 8D regular turbine spacing (inter-turbine spacing equal to 8 rotor diameters, in both prevailing and transverse directions), in a square layout;
- 10m/s mean wind speed;
- 1.5m long-term average significant wave height (Hs);
- 30m water depth;
- Monopile foundations;
- 50 nautical miles (approximately 90km) from construction port and O&M port;
- 50km offshore export length;
- 25km onshore export length.

It should be noted that the Load Factors detailed in this report would be expected to vary if project conditions deviated from these assumptions – for example, an offshore wind farm in a location with mean wind speed greater than 10m/s would be expected to yield a Load Factor greater than the values detailed below for a given technology.

8.3 Different Technology Scenarios Assumptions

The following assumptions have been made in the different technology scenarios:

- The baseline WTG is a theoretical turbine of 9MW capacity, a 175m rotor and a direct drive generator. This is broadly comparable to the current state-of-the-art, adjusted for consistent power density (see below).
- Approximately constant power density of 380W/m^2 for current and future conventional WTGs. This removes from the analyses any variability related to OEM preference and enables like-for-like comparison between scenarios and hence the impact on Load Factor of each specific technology. 380W/m^2 represents a reasonable average for current offshore turbines, and approximately the power density that is expected to yield the lowest cost of energy for offshore sites with good wind resource.
- The two-bladed WTG scenario assumes turbine design parameters similar to that of the 2-B Energy design (6MW capacity, 140m rotor diameter).
- WTG technical availability and annual OpEx has been adjusted by scenario, based on O&M modelling with the project configuration shown above. Availability has been assumed to vary both with O&M strategy and with project configuration, with wind farm availability ranging from 93.7% to 96.8%. This approach was taken to capture the advantages of future turbines, which are expected to offer improvements in OpEx as well as CapEx.
- WTG performance improvements and blade extensions are considered to increase the coefficient of performance of the turbine; all other parameters remain constant.
- Asian WTGs are expected to be made commercially available at reduced CapEx, in comparison with those from European OEMs, and require slightly increased O&M (noting that this could be mitigated in practice via warranty agreements). OpEx was increased by approximately 5%, to reflect higher failure rates, based on O&M modelling.
- Service Operation Vessels (SOVs) are the default O&M strategy, reflecting current industry practice as well as the impact of offshore wind farms becoming larger and farther from shore.
- “Capable” CTVs include vessels such as the Umoe Mandal Wavecraft, which offer significantly increased transit speed (up to 35 knots) and increased accessibility (up to 2m Hs).
- The floating wind scenario is assumed to use a semi-submersible foundation, such as that offered by Principle Power, which are manufactured in a serial production facility to a standardised design. Turbine installation is assumed to occur in port, with the complete foundation-turbine structure then towed to site to complete installation.
    - A mean wind speed of 10.5m/s was applied to the floating wind project, to reflect potential deployment in UK locations with better wind resource but remain realistic with respect to project construction feasibility.
- Advanced control systems and optimised layout design result in increased array efficiency, with the magnitude of the uplift based on that calculated by the baseline model and adjusted for expected increases suggested by related work in these two technology areas. In each case, an increase of approximately 1% was applied.

The estimated impact of each technology (such as increased energy production) is input into the model, such that the change in CapEx, OpEx or turbine performance is then captured in the LCoE calculation (see below) and the calculation of annual energy production (in turn used to calculate Load Factor).

8.4 Economic Assumptions

The following economic assumptions have been made in the economic model used to calculate levelised cost of energy:

- A simplified discounted cash flow model, based on IEA 2015.
- Discount rate = 5%.
- 25-year project lifetime.
- Construction CapEx is assumed to occur in a single year from the perspective of the financial model, noting that in practice construction is likely to occur over multiple seasons (this approach removes the impact of specific financing strategies).
- CapEx is funded by 100% equity i.e. financing costs are excluded.

It is noted that variation in these factors may affect LCoE; however, this variation is a financial (rather than technical) aspect and hence outside of the scope of this study. Indicatively, these factors would be expected to have the following impact on LCoE:

- Increased discount rates (for example, for riskier technologies or in less-developed markets) would increase LCoE;
- Increased project lifetime reduces LCoE, although the effect is relatively small;
- Project construction across multiple seasons would be expected to increase LCoE, by requiring funding to be available for a longer period prior to the generation of revenue. However, this impact could be partially mitigated by phased construction enabling earlier generation whilst construction is ongoing;
- Debt funding would be expected to increase LCoE through increased cost of finance. Early offshore wind farms were funded from equity, and this practice may return as costs continue to fall.

8.5 Modelling results by future technology

The modelled Load Factor and Levelised Cost of Energy results for the application of each future offshore wind technology to the hypothetical wind farm in shown in Table 8-1.

The results show that each technology has a relatively small impact on Load Factor, but that significant reductions in cost of energy are achieved; in a competitive (auction) market, this would be expected to yield increased total installed capacity. The application of all complementary technologies yields the highest Load Factor and lowest cost of energy, and represents the approximate upper and lower bounds respectively for the offshore wind industry to 2035. The "combined" model included the cumulative impacts of all relevant technologies, for example the increases in energy production from large turbines, optimised layout design, advanced control and increased availability, with reduced CapEx relating to turbine size and reduced OpEx due to optimised O&M strategies and reduced lost production.

Technology	Load Factor	LCoE (£/MWh)
Current technology	42.0%	121.0
Baseline	49.7%	48.0
Turbines: next-generation 10MW+ WTGs	50.3%	45.4
Turbines: next-generation 15MW WTGs *	51.1%	44.8
Turbines: two-bladed turbines	47.0%	51.2
Turbines: WTG performance improvements *	50.3%	47.4
Turbines: blade extensions	50.3%	47.4
Turbines: Asian WTGs	48.9%	48.5
O&M strategy: SOVs *	49.7%	48.0
O&M strategy: capable CTVs	49.2%	47.4
O&M strategy: helicopters + capable CTVs	49.4%	47.2
Design: floating wind	51.0%	58.3
Design: advanced control *	50.4%	47.2
Design: layout design *	50.2%	47.5
Combined: all complementary technologies	**52.9%**	**43.2**

* Technologies included in "Combined" case

Table 8-1 Modelling results by technology

The benefits of the technologies shown above are expected to be realised in stages, for example with 10+MW turbines available in the mid-2020s and those in the 15MW range in the early 2030s; similarly, incremental advances are expected in blade technology, O&M and control, with some gains occurring in the medium-term and the full benefit expected in the longer-term. Accordingly, Load Factors for new-build offshore wind farms of approximately 48-49% are expected in 2020, rising to 50-51% in the mid-2020s and then to 52-53% by the mid-2030s following the introduction of all expected technologies.

Larger wind turbines are expected to yield increased Load Factors and reduced cost of energy, both from the expected next generation of turbines in the 10-12MW range, and then another, albeit smaller, improvement to the 15MW-scale turbines that are expected to be commercially available by 2035. These increases result from a combination of factors, including reduced wake losses due to the reduced turbine count, access to higher wind speeds through increased rotor height, and reduced balance of plant costs. Such turbines may also be provided with more efficient rotors and improved control systems, further adding to energy production and therefore Load Factor. Wind farm operation is also continually improving, with increased turbine availability and reduced downtime also contributing to increased energy production and a consequent reduction in cost of energy.

Two-bladed turbines are less aerodynamically efficient than three-bladed versions, and hence the Load Factor predicted from a wind farm comprising such machines is comparatively lower at 1 to 3% lower than three-bladed turbines. Offshore wind turbines from Asian manufacturers are perceived to exhibit lower reliability and availability, and hence the Load Factor from these machines is also lower – although reduced CapEx may make the cost of energy competitive.

Floating offshore wind farms are likely to be deployed in locations where conventional bottom-fixed technology is not feasible, where better wind resource is available. As a result, higher Load Factors are expected, although floating wind is expected to demonstrate reduced availability due to the complexity of component change-out, which counters some of the increase in Load Factor. Floating wind is not expected to compete with bottom-fixed wind in locations where the latter is technically feasible, but the benefits of standardised manufacture and onshore assembly mean that costs should reduce to broadly-competitive levels and commercial deployment in favourable jurisdictions is expected by 2035.

It should be noted that these results are dependent on the assumptions listed in Section 8.2, and current economic parameters such as the cost of fabricated steel. Project development in particularly favourable locations, such as those with exceptional wind resource, and/or significant advances in supply chain capability and hence further balance of plant cost reduction, could result in projects generating at a lower cost of energy, and higher Load Factor, than those shown in Table 8-1.

8.6 Industry survey

A survey was undertaken of the offshore wind industry to gain insight into the forecasts and expectations of industry stakeholders with respect to future offshore wind technology. Detailed interviews were conducted with personnel from major equipment OEMs, offshore wind project developers, transmission asset owners, offshore designers and R&D institutions. It should be noted that some respondents participated under condition of anonymity.

The survey participants were in general agreement with the assumptions and estimates of Load Factor and LCOE for each of the modelled technology scenarios. The key elements from the responses from the industry survey are summarised below, by technology. The survey questions are shown in Appendix A.

Overall, the industry expects that new technologies will be deployed in future offshore wind farms, and that Load Factors will increase, and cost of energy reduce, as a result. The industry considers that the future technologies most likely to be commercially deployed by 2035 are larger turbines and more advanced software systems, with floating wind farms also expected within that timeframe in suitable jurisdictions. The industry also expects evolution of current technologies to dominate, such that more novel technologies are not expected to gain much traction in mainstream offshore wind markets.

8.6.1 10MW+ offshore wind turbines

The following points highlight the key elements of the interviewees' responses:

- The next generation of offshore wind turbines (10MW+) are expected to be deployed between approximately 2022 and 2025.
- It can be assumed the OEMs will try, where possible, to use existing proven technology i.e. turbine technology will be an evolution, not a step change.
- The deployment of new turbines requires a level of testing to provide confidence in new models. Looking back, relatively little prototyping was done.
- A new turbine platform is typically deployed with circa 8,000 hrs of testing. A significant amount of testing and prototyping can be expected.
- Project risk: in isolation, using larger WTGs is seen as presenting increased project risk, but as more are deployed this will not represent a significant impact on projects. However, this will also not be the case in a more competitive environment. In the future, you can expect there will be limiting construction and foundation risk. Can't see being able to pricing in more project risk. With the right measures this will be overcome.

- New turbine models undergo a regular / common phase of testing, and this can be assumed to be the case for the 10MW+ offshore turbines. Testing programmes and equipment will be standardised. This is common practice at the moment in Europe.
- New turbine designs will be first deployed onshore, then possibly near shore at suitable locations, then offshore. This could pose logistical challenges for the very large machines.
- The industry will try to reduce risk by applying a standard testing approach. There is increased risk using 10MW+ turbines for medium-sized (500MW) projects. In particular, the reliability of "new" technology is a potential risk.
- The development of larger offshore wind farms will require the balancing of risk from O&M, new tools, new vessels etc. Any new technology brings inherent risk, but this can be mitigated with appropriate testing and verification, in addition to normal type certification.
- Current indications show an upward trend in Load Factor using larger machines. Within the 2035 timeframe, given the development time required, new turbines are expected to reach approximately 15MW capacity. The WTG CapEx may be higher, but this can be outset by the relative increase in energy production using these larger offshore turbines.
- The increasing size of offshore turbines is expected to plateau - looking back at trends, in the mid-2000s turbines were of 3-4 MW capacity; in 2015, 6MW to 8MW. It is expected that 2023-2025 will see 10-15 MW turbines, but that 2030 might not see 20MW machines. From a supply chain point of view, the main question is logistical: can turbines of these magnitudes be manufactured and installed? There could be early development work around 2035 of a 20+MW turbine, although it may not be commercial available by that time.
- It is expected that 10MW+ turbines will offer the potential to reduce overall project costs, through reductions in balance of plant CapEx and increased energy production. Downtime, maintenance changes with 8MW to 15MW. Dynamic of larger WTG is uncertain. Maintenance cost will come down. Reliability of components is an unknown. There are potential questions of electrical infrastructure. Outside technical parameters such as location of sites, and types of companies developing / owning / operating, for example O&G companies interested in investing in OWF will have a healthy balance sheet to potentially successfully build and operate these GW plus offshore wind farms.

8.6.2 Two-bladed offshore wind turbines

With respect to the viability of two-bladed offshore wind turbines, the interviewees offered the following key responses:

- Two-bladed turbines are not considered likely to achieve commercial viability by 2035 (or that this has a very low probability of occurring). Increased operating noise is not seen an issue offshore; however, potential issues with turbine rotor balance would need to be addressed and potential blade erosion (due to higher rotational speeds) may also be an issue.
- Two-bladed turbines may have similar Load Factor to three-bladed turbines. Achieving commercial availability would require a tier one OEM to be convinced that there is potential and invest in development accordingly. It is considered possible that installation occurs in some specific countries, where the technology is suited to specific conditions.
- Offshore wind is already a very challenging environment, and it is not prudent to add another layer of risk. In typhoon-affected areas, two-bladed turbines may be suitable due to their

inherent protection against extreme conditions in the "parked" configuration. In pure CapEx terms, cost savings from three to two blades it is not expected to be significant.

- Some consider that two-bladed turbine technology has something to offer, but that it will not play a dominant role. It is more likely be seen as part of a research / proof of concept project.

8.6.3 Turbine performance and blade improvements

The interviewed stakeholders offered the following responses in relation to increased turbine performance and blade improvements such as extensions:

- Blades will feature increased proportions of carbon fibre reinforced composite materials, with research into lighter components continuing. For 10 to 15MW machines, it is expected that carbon fibre will replaced some of the glass fibre-based material – this will occur in a process of evolution rather than revolution. Blade leading edge erosion has affected the industry in recent years, and is a reminder to the industry to keep progressing blade design and technology.
- Performance-enhancing technology cannot easily be retrofitted on existing offshore turbines, but it is expected that future 15MW capacity turbines may have more room for retrofitting / modification. There is a drive within the industry to find efficient ways of improving turbine availability; several parties are pursuing this.
- Improved blade aerodynamics are expected to improve Load Factor by a magnitude of less than 1%, as long as blade condition is regularly monitored and maintained.
- It is expected that modular and/or textile blade designs will become more common, and that carbon fibre will be increasing widely used. There is an overall industry drive to make blades lighter, which would be expected to increase turbine performance.

8.6.4 Novel technologies

Novel offshore wind technologies, such as kites or multi-rotor machines, elicited the following responses from the interviewees:

- Kite concept may be something of interest when considering re-powering of existing offshore wind farm sites. However, it is not considered likely that airborne / multi-rotor concepts will achieve commercial viability on commercial projects by 2035.
- The use of particularly novel technologies is primarily a matter of appetite for risk, as such technologies are unproven. These may be suitable for remote islands, for example, rather than established offshore wind markets.

8.6.5 Asian turbine OEMs

As the global offshore wind industry expands, new entrants are expected in the turbine market including those from lower-cost jurisdictions. The interviewees provided the following views on turbine supply from Asian OEMs:

- Asian OEMs will need to prove their reliability first to gain the confidence from the finance community. They may potentially look to establish a joint venture partnership with an established European turbine OEM, entering the global market that way.
- Reliability is the biggest challenge; the key question for project developers will be how cheap must the hardware be for it to be worth the perceived increased risk due to the lack of a manufacturer track record. The perception is that Chinese OEMs have questionable reliability, which would negatively impact production and therefore presents a risk to a project.

- Local content in projects is increasingly a focus area and requirement; this is a potentially significant aspect in Europe, Asia and the US. Due to the proportion of project CapEx which is fulfilled by turbine supply, the use of “local” turbines would significantly increase the proportion of local content.
- To date, there has been a strategy by Asian OEMs to keep their focus on local markets in the first instance i.e. the Japanese and Taiwan markets.
- Asian OEMs have proven to be very competitive in their home market, but not yet competitive in global market. This is only expected to change if the perceived reliability challenges can be mitigated, either via track record or contractual means.

8.6.6 O&M technologies

Recent offshore wind projects have deployed a range of O&M technologies in efforts to maximise availability and minimise costs; the stakeholders’ views on O&M technologies are as follows:

- Fuel consumption by SOVs needs to be carefully studied, as it may be that an SOV has higher consumption than equivalent CTVs throughout the entire life of the wind farm.
- SOV designers and operators are investigating greater use of hybrid powertrains, including battery energy storage, to reduce fuel consumption and have a "greener" O&M operation.
- The offshore wind industry would like to limit the use of helicopters, due to the potential risk to life. Offshore wind has taken note of the recent incidents with helicopters in the offshore oil and gas industry in the UK.

8.6.7 Floating wind turbines

The interviewees’ views on floating offshore wind are as follows:

- Floating WTGs are an interesting technology that is fast growing, and will be more attractive in countries where the water depth is not shallow near shore, or in order to access better wind resource. Floating wind will bring installation and O&M challenges, for example in deep water where jack-up vessels cannot operate.
- It is expected that the Load Factor of floating wind farms will be higher than that of bottom-fixed projects, based on the assumption that floating turbines will be sited at locations with higher wind resource.
- From a technical point of view, there is a barrier between turbine OEMs and floating platform technology companies. Overall, floating wind could benefit from having some standardised approach to turbine control.
- The industry expects that floating wind will be deployed on commercial projects in approximately 2023/2024, although this depends on location, countries, local rules and regulations. These may slow down the deployment, and there are also barriers on the finance side. The industry as a whole needs to prove the concept of floating wind, including reliability, and the potential risk reduction of assembling the whole WTG onshore.
- Other stakeholders consider that commercial floating wind is still ten years away. The most likely locations for initial deployment include Japan, or countries which are interested in using floating wind to provide power to offshore oil and gas facilities.

- Installation cost reduction is key, and CapEx levels are expected to be largely similar to jacket and monopiles in deeper waters, for example at 50m. Floating wind platformshave the potential to be supplied globally, using a standardised design and serial production to reduce costs.

8.6.8 Wind farm control and layout design

The stakeholders offered the following responses with respect to the future use of improved wind farm control and design technologies:

- Wind farm control: increased and/or more effective use of large-scale ("big") data is expected to become common, and support the increase of technical availability and in turn achieve higher Load Factors.
- Having an optimised wind farm layout (i.e. non-grid layout) is seen as a potential way of reducing WTG wake effects, and thus increasing the Load Factor.

8.6.9 Electrical transmission system

The survey elicited the following responses on the topic of offshore wind farm electrical infrastructure:

- There has been a move from 33kV to 66kV intra-array collection cabling as offshore wind turbines have increased in capacity. Recent CfD-winning projects are expected to use 66kV cabling, and it is also expected that 66kV will become the default option.
- Cables are rated to operate at 100% LF constantly.
- Cables also have an alternative for dynamic rating at 80% of Load Factor and 20% generated through heat from the cables.
- There is potential for further cost savings from dynamic rating. Part of the reason why this is not currently widely used is due to the requirements set by Ofgem. In onshore wind, cables are rated at 100% Load Factor.
- Cables are designed to have a high availability (typically 98.8% or above), therefore it is assumed that there is little room for further significant availability improvements.
- Damage to export cables has unfortunately occurred more frequently than previously assumed. More cost benefit analysis is being done to obtain the best compromise and inform the design of future cables.
- In terms of innovations, the Siemens offshore transformer module (OTM) is gaining some market traction. It has a building block concept, it has a robust and compact design, simplified for installation with low maintenance. All this helps bring down the cost.
- By 2035, it is expected that HVDC will be more commonly used as offshore wind farms move further offshore. There will likely be a meshed system, and greater interconnection. The current OFTO regime gives little to no incentives for owners or operators to move into this space.
- In a UK post-CfD and OFTO regime, local storage might be invested in by developers / owners. This would open up additional grid services, and enable electricity to be sold at periods of higher price / high demand, maximising the value of the generated energy.
- It is expected that offshore wind farm owners will invest to maximise use of the grid connection to add additional revenue, via the provision of ancillary services to the grid and the installion of more equipment onshore, such as battery storage. The current OFTO regime, where the payment meter is offshore, gives no incentives for this investment.

9 RESULTS

The impact of three categories of offshore wind technologies, detailed in Section 5 to 7, have been modelled to assess their potential impact on Load Factors for projects in the timeframe from 2015 to 2035. The overall results of analysis are summarised below for the following categories:

- Wind turbine technology;
- Wind farm design; and
- Operations and maintenance (O&M) technology.

The combined results are based on an assessment of the impact of the various offshore wind technologies, accounting for uncertainties in both timing and Load Factor assumptions. The modelled Load Factors are based on assumptions detailed in Section 8 and the resulting improvements in Load Factor for each technology are summarised in Section 8.5.

The lowest levelised cost of energy future offshore wind technologies will be adopted over the timeframe from 2015 to 2035. LCoE is driven by the combination of Load Factor and lifetime costs of technologies. Therefore, the lowest levelised cost of energy technology could result in either an increase or decrease in Load Factor. The impact of LCoE is considered in the results presented include the potential upper and lower range in Load Factor over the period 2015 to 2035. The upper and lower results are based on uncertainties in the assumptions detailed in Section 8.3 and the results of the industry survey detailed in Section 8.6 and reflect that future technologies with the lowest LCoE could results in an increase or decrease in Load Factor.

A sensitivity analysis was undertaken to estimate the impact on Load Factor to the modelling input assumptions to estimate the upper and lower range. The upper and lower range is based on 10% and 90% probability of exceedance for Load Factor, accounting for the combined impact of all complementary technologies and the year of commercial deployment.

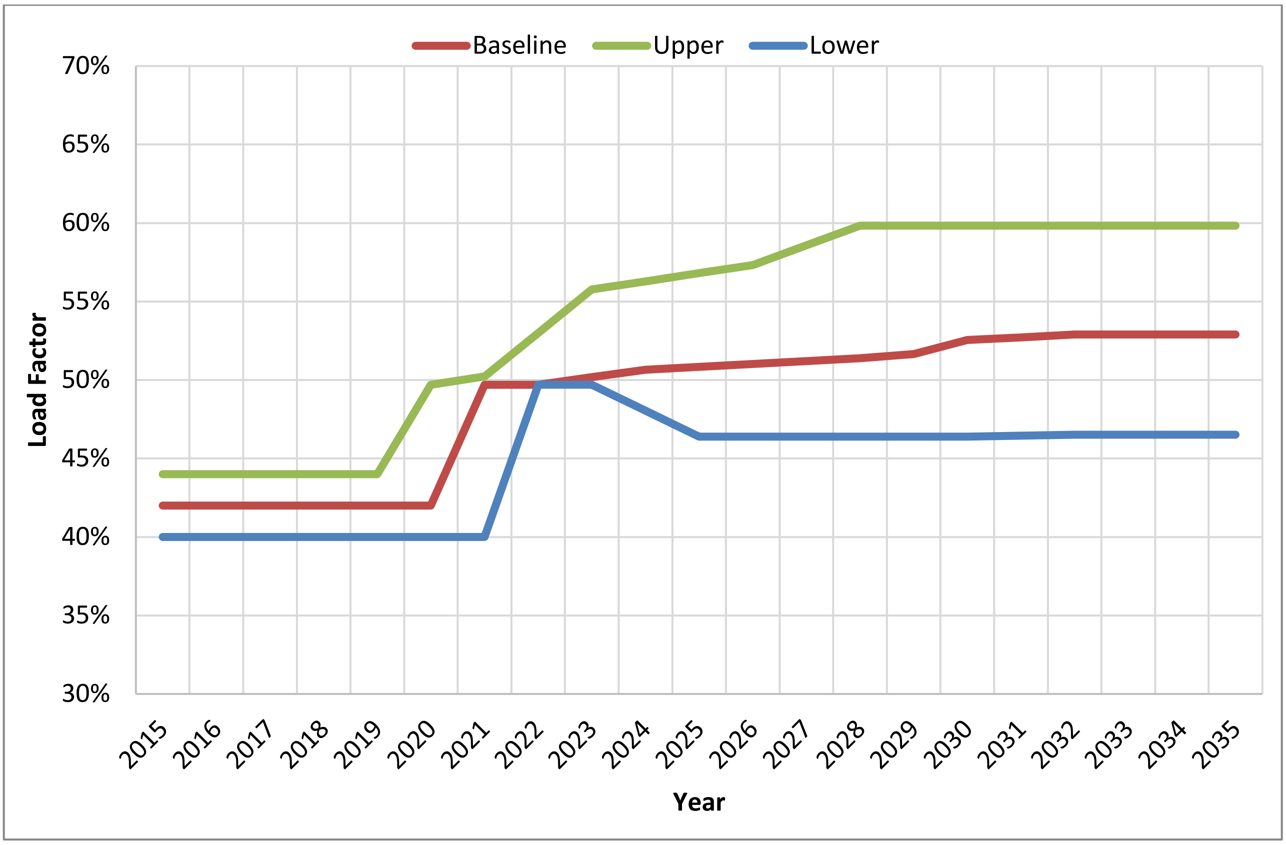

Figure 9-1: Projection of estimated Load Factor for future offshore wind farms to 2035

Figure 9-1 presents the estimated projected Load Factors for future offshore wind farms in the UK, for the period to 2035; lower and upper bound estimates are also shown, representing approximately P10 and P90 confidence levels regarding the timing and impact of the deployment of future technologies in UK offshore wind farms. Load Factors are expected to continue to increase in the period to 2035, largely driven by technological development.

The notable "jumps" in Load Factor, which occur at approximately 2023-4 and 2030-1 for the baseline case, are driven by the introduction of new turbine designs. These are expected to feature step-changes in generator and rotor size, compared to their precedessors, which result in increased energy production and availability. Alongside these steps, technological advancements in blade design and performance, O&M technology and technical availability, and wind farm design and control are expected to occur incrementally over the period; these contribute to the more gradual increases in Load Factor that occur between the introduction of new turbines.

The "lower" bound projection in Figure 9-1 represents the progression of Load Factor in a scenario in which technological development is slower and less effective; for example, in which the development phase for future turbines results in a lower increase in Load Factor, or takes longer and hence commercial deployment of the new machine is delayed. Wind farm technology is already well-developed, and future gains in aspects such as layout design and blade efficiency may be increasingly difficult to obtain, such that the impact of these technologies is less significant than assumed in the baseline scenario. There may also be practical and/or economic limits to some technologies, via diminishing returns; for example, achieving turbine availability in excess of approximately 98% is unlikely to be economically beneficial, and hence the contribution to increasing Load Factor from the O&M strategy would be expected to tail off when such values are reached. The lower bound projection in Figure 9-1 is similar to the baseline estimate for the period to 2022-3, as the figure is based on project commissioning dates – this is the time at which offshore wind projects which won CfDs in 2017 will enter commercial operation, and as the technology proposed for these projects is known, they are considered to represent both the baseline estimate and the lower bound.

The notable "reduction" in Load Factor evident in the "lower" bound projection, occurring in 2023-5, is due to uncertainty in the characteristics of next-generation turbine designs which leads to the lowest cost of energy. If these turbines exhibit higher power density than current best-in-class machines, offshore wind farms deploying these turbines would be expected to yield lower Load Factors as well as lower lifetime costs.

The uncertainty in the efficacy and timing of future technologies also applies to an "upper" scenario, which is also shown in Figure 9-1. The considerable technical resources of turbine OEMs may enable the development and testing phase of future turbines to be compressed, such that they are commercially available earlier than currently expected; similarly, more advanced design, modelling and control techniques may enable the expected gains in these areas to be greater, and available sooner, and hence Load Factors would increase more quickly than the current expectation.

Based on an uncertainty analysis of the Load Factor modelling assumptions, as detailed in Section 8.1 to 8.3, the uncertainty in Load Factor has been modelled for each technology type as presented in Table 9-1. A Load Factor sensitivity analysis was undertaken to model the variation in Load Factor due to the uncertainty in the input assumptions detailed in Section 8.1 to 8.3. The key findings from the load factor sensitivity analysis and resulting uncertainties are summarised below:

- The Baseline mean wind speed assumption of 10m/s was estimated to have an uncertainty of 5%, resulting in a variation in Load Factor of 2.4-2.6%. The mean wind speed uncertainty has been accounted for under the wind turbine technology uncertainty;
- The wind turbine technology power density assumption of 380W/m^2 was estimated to have an uncertainty of 15-20%, as this relates to turbine manufacturer design choice. Variation in the power density assumption was modelled to result in a variation in Load Factor of 2.7-3.3%;
- Additional variation in turbine technology Load Factor was identified due to array efficiency, wind turbine performance and wind farm availability, which resulted in a total modelled estimated wind turbine Load Factor variation of 3.9-4.5%;
- O&M strategy was estimated to result in an uncertainty in wind farm availability of 0.7%, which results in a modelled O&M strategy Load Factor variation of 0.7%; and
- Design technologies were estimated to result in uncertainty in turbine performance and array efficiency resulting in a Load Factor variation of 1.0-2.7%;

The "combined" model included the cumulative impacts of all relevant technologies, for example the increases in energy production from large turbines, optimised layout design, advanced control and increased availability, with reduced CapEx relating to turbine size and reduced OpEx due to optimised O&M strategies and reduced lost production.

Technology	Load Factor	Uncertainty
Current technology	42.0%	-
Baseline	49.7%	-
Turbines: next-generation 10MW+ WTGs	50.3%	3.9%
Turbines: next-generation 15MW WTGs *	51.1%	4.6%
Turbines: two-bladed turbines	47.0%	4.3%
Turbines: WTG performance improvements *	50.3%	0.3%
Turbines: blade extensions	50.3%	0.3%
Turbines: Asian WTGs	48.9%	4.5%
O&M strategy: SOVs *	49.7%	0.7%
O&M strategy: capable CTVs	49.2%	0.7%
O&M strategy: helicopters + capable CTVs	49.4%	0.7%
Design: floating wind	51.0%	2.7%
Design: advanced control *	50.4%	1.1%
Design: layout design *	50.2%	1.0%
Combined: all complementary technologies	52.9%	6.9%

* Technologies included in "Combined" case

Table 9-1 Modelling results and uncertainty by technology

It should be noted that the increases in Load Factor detailed in this report are based on assumptions regarding turbine OEM designs and UK wind farm characteristics, as detailed in Section 8, and therefore that absolute Load Factors demonstrated by future UK wind farms would be expected to deviate from the values described in this document. For example, deployment of offshore wind in sites with a long-term mean wind speed in excess of 10m/s would exhibit increased Load Factors and reduced cost of energy relative to the estimates detailed above.

Similar progression is expected in the cost of energy from future offshore wind farms, driven by both new technologies and advances in the supply chain as the global industry grows. Future offshore wind farms are expected to continue the trend of reduction in cost of energy shown by the industry to date, albeit at a reducing rate; this is likely to comprise both step-changes with the introduction of new turbines and incremental advances from supporting elements.

10 RETROFIT OF TECHNOLOGIES AND ENERGY STORAGE

As part of the study the opportunity to retrofit the future technologies identified in this study to existing operational wind farm has been explored.

10.1 Retrofit

Whilst the technologies described in the preceding sections are primarily considered for new-build projects, some would be theoretically feasible for retrofitting to existing offshore wind farms. For example, aerodynamic add-ons and blade tip extensions could be added to blades in service, and modifications to control software are relatively simple to implement. Furthermore, the technologies that do not directly impact structural design could be "retrofitted"; for example, revising a project's O&M strategy to take advantage of advances in vessel capability is both technically feasible and is being seen in the industry.

However, the practical challenges and costs associated with offshore working mean that retrofit is considered unlikely; a retrofit campaign would require the removal of each blade and the use of specialist vessels, and hence significant downtime for what would be expected to be a marginal benefit to wind farm performance. It should also be noted that the retrofitting of some technological improvements, such as changes to blade aerodynamics, may affect the operating conditions of a turbine, such as by increasing loads imparted by the turbine onto the foundation, and hence impact the fatigue life of the foundation; therefore, whilst technically feasible, this would also be considered unlikely.

The more integrated technologies, such as drivetrain technologies, would not be suitable for retrofit; likewise, those which differ from the initial technical concept (i.e. currently three-bladed, horizontal axis, upwind turbine). Overall, it is considered unlikely that widespread retrofitting of the majority of the future offshore wind technologies identified in this report, other than software updates and alternative O&M strategies, will be common.

10.2 Energy storage

Energy storage systems take in electrical energy, from either a generator or the grid, effectively "convert" this energy into another form (chemical, kinetic or potential) to store it, and then release it via reversal of the conversion mechanism in order to produce electrical energy. A wide variety of storage technologies are in development, from lithium-ion batteries to power-to-gas; each has distinct advantages and disadvantages, and there has been little technological convergence to date.

Energy storage enables production to be temporally shifted, typically to be sold at times of higher prices, or to reduce potential curtailment in the event of oversupply. The variable nature of renewable energy makes it a prime candidate for being combined with energy storage, although it is noted that standalone storage systems are also becoming common. Energy storage is being considered by the offshore wind industry, for example at the Hywind Scotland project /53/, although there are no operational systems at the time of writing.

Battery energy storage systems are typically used to provide grid services, such as frequency regulation, either alongside time-shifting or as the primary revenue source. In such cases, coupling of battery storage systems to offshore wind farms would mainly be due to the grid connection, and would be expected to have minimal impact on the operation, and hence Load Factor, of the wind farm.

Any energy storage system incurs losses in operation, meaning that more energy is consumed than subsequently released (the "round-trip efficiency"). Lithium-ion batteries typically exhibit round-trip efficiencies of greater than 90%, whereas power-to-gas systems would be expected to yield less than 50% efficiency. Therefore, any storage system directly coupled to an offshore wind farm would have the effect of reducing the wind farm's Load Factor, by the proportion of the round-trip efficiency (if the net energy production is measured at the grid connection point, downstream of the storage system).

It would also be possible to incorporate energy storage into an offshore wind farm which is "overplanted" (i.e. installed capacity is greater than the capacity of the grid connection), and overproduction is managed by the storage system so as to be exported when generation from the wind farm drops below the capacity of the grid connection. Due to the large scale of offshore wind farms the storage system would have to be large-scale, and due to the duration of periods of potential overgeneration or low wind periods may also require to store the excess energy for a long period of time before discharge and hence demonstrate low utilisation. This presents both technical and economic challenges to an energy storage system, and hence is considered unlikely; such an approach may be better suited to solar PV generation, for example, where the more frequent variation in output enable higher utilisation of the storage system.

An alternative scenario would involve an energy storage system connected at the same grid connection point as an offshore wind farm, but with the two systems operating independently; this increased usage of the grid connection is more economically efficient. The Load Factor of the wind farm would therefore be unaffected by the storage system, as the metering point for the wind farm would be distinct from that of the energy storage system.

Commercial deployment of this latter scenario is considered likely in the to-2035 timeframe of this report, as the commercial attractiveness of energy storage systems continues and the sharing of grid connections enables development costs to be reduced. However, the direct coupling of energy storage with offshore wind farms is considered unlikely in that timeframe, hence the overall view is that energy storage will have negligible impact on the Load Factors of offshore wind farms to 2035.

11 APPLICABILITY OF TECHNICAL ADVANCEMENTS TO ONSHORE WIND

The scope of work involves the assessment of the potential for technology transfer from the offshore wind industry to onshore wind, and by association the extent to which onshore wind Load Factors may vary due to technological impact. It should be noted that a specific study into, or detailed modelling of, onshore wind Load Factors has not been undertaken, but a qualitative comparison between the onshore and offshore sectors is made where relevant. Section 11.1 details the potential technology transfer between offshore wind and onshore wind for those future technologies identified in /54/, whilst Section 11.2 takes a more general view of the technological trends expected in onshore wind over the forthcoming two decades.

11.1 Technology transfer potential

Ten offshore wind technologies have been identified as having the potential to be deployed on commercial-scale offshore wind farms in the period to 2035 /54/; these technologies are expected to increase the Load Factor of future offshore wind farms from that of current projects, as well as reducing the cost of energy.

Offshore wind technology originally evolved from the onshore wind industry, although as the former has developed some technical divergence has occurred. However, there is still significant commonality between the two variants of the wind industry, and therefore it is of interest to ascertain the extent to which technology transfer may occur from offshore wind back to onshore wind, and therefore in turn to which the Load Factor of future onshore wind projects may change.

The identified offshore wind technologies are as follows:

- 10MW+ wind turbines;
- Two-bladed turbines;
- Turbine performance and blade improvements, including blade aerodynamic additions;
- Novel technologies, such as airborne turbines and multi-rotor concepts;
- Asian turbine OEMs;
- O&M technologies i.e. specialist vessels;
- Floating wind turbines;
- Wind farm control;
- Advanced layout design;
- Electrical transmission system.

Floating wind turbines have been excluded from this report due to the offshore-specific nature of the technology; the potential for technology transfer to the onshore wind industry, for the remaining technologies, is discussed in the following subsections.

11.1.1 10MW+ offshore wind turbines

A 10MW offshore wind turbine would be expected to feature a rotor diameter in excess of 180m, with blades approaching 90m in length and a maximum tip height of around 200m. Offshore wind turbines are expected to grow larger than this by 2035, by which point 15MW machines are expected, featuring blades of around 110m in length and tip heights approaching 250m.

The logistics of these parameters mean that deployment of similarly-sized turbines onshore is considered unlikely; blades would likely become too large to be transported by road, and the visual impact of very large turbines on nearby settlements would also be significant. It is believed that turbine OEMs are pursuing segmented blades for onshore wind turbines, which can be transported to site in multiple sections before being joined together prior to installation; this will improve transportation logistics, although width restrictions on blade root diameter for road transportation may still apply to the root section.

However, the trend of increasing turbine scale is also evident in onshore wind, and is expected to continue. Current onshore turbines are typically around 3MW, but turbine manufacturers are developing larger machines for the onshore market and project developers are planning for such machines to be used. Concerns around transportation logistics and visual impact remain, and may pose challenges for some projects which are targeting the use of the next generation of onshore turbines, but increase in turbine size into the 4-5MW range is expected and should be achievable for some UK projects.

Increases in the size of onshore turbines is expected to yield similar benefits to a similar trend offshore, in that Load Factors would likely increase due to the increased energy production, and cost of energy reduced due to lower balance of plant CapEx and project OpEx.

Onshore turbine manufacturers are also introducing variants of their products designed specifically for lower-wind sites, in which larger rotors are installed – this reduces the power density of the turbine, improving its low wind performance and increasing its Load Factor. Use of such turbines at sites with good wind resource would result in increased Load Factor compared to existing projects, although these turbines are designed for use at lower-wind locations where their impact may be to reduce the magnitude of the reduction in Load Factor, rather than to increase it in absolute terms. In the UK, where a reasonable proportion of sites with good wind resource have already been developed, future onshore wind projects may make use of these optimised turbines to enable economically-viable development of lower-wind locations.

Larger onshore wind turbines are already in development, and as these demonstrate smaller increases over the current state of the art it is expected that their deployment would be realised more quickly than for the next generation of offshore turbines. Similarly, existing technology, for example in terms of drivetrain concept and blade materials and design, is expected to suffice for the upcoming larger onshore turbines, and hence these machines will be evolutionary in design and build upon existing track records to minimise the technology risk associated with new turbines.

11.1.2 Two-bladed wind turbines

Design convergence has occurred in the wind industry, both onshore and offshore, in the selection of three-bladed rotors. Two-bladed turbines have been demonstrated, and are still the subject of on-going development work in an effort to exploit some of the inherent potential advantages over three-bladed designs, such as reduced blade costs and simplified O&M.

However, two-bladed turbines typically operate at higher rotational speed than three-bladed equivalents, which generates more noise; noise is more of a concern onshore than offshore, as it can affect planning restrictions. Furthermore, the visual impact of two-bladed turbines is generally considered more significant than that of three-bladed machines, due to the way in which the blades pass into and out of the field of vision when rotating. As a result, two-bladed turbines are not expected to become widely used onshore.

As with offshore variants, achieving commercial viability of two-bladed onshore turbines would require a tier one turbine manufacturer to invest in the development of a suitable machine, instead of further development in three-bladed designs. Given the advantages of three-bladed turbines for onshore wind, this is considered unlikely, and is the most significant barrier to the use of two-bladed turbines onshore.

11.1.3 Turbine performance and blade improvements

Onshore and offshore wind turbines are similar in configuration, with both industries having largely converged on three-bladed horiztonal-axis turbines; therefore, performance improvements suitable for offshore machines would be expected to also be applicable to onshore turbines, pending the different restrictions on onshore technologies, such as noise emissions and visual impact.

Advances in blade materials are expected to apply to onshore turbines as well as offshore wind, as lighter-weight blades would improve turbine performance in onshore-scale turbines, even where the improved structural properties are not necessarily required to achieve increasing blade size. Blade leading edge erosion is a challenge for the onshore wind industry as well as for turbines offshore, and hence improvements in blade leading edge protection are expected to be applied to onshore turbines as well; the result of such improvements would be reduced downtime, and hence increased Load Factor, as well as reduced OpEx and therefore cost of energy. Improvements in turbine performance and downtime resulting from reduced leading edge erosion would be expected to yield increases in Load Factor of up to 1% and a similar proportional impact on LCoE.

Performance-enhancing technology is also potentially applicable to onshore turbines, although similar barriers regarding retrofit apply as to offshore machines – retrofitting is technically possible, but may be subject to practical limits such as tip clearances and increased loads, which is considered likely to limit the extent to which retrofitting to existing turbines is pursued. It is expected that onshore turbines will feature more efficient rotors, including through the use of aerodynamic devices and add-ons, which will increase energy production and Load Factor. The magnitude of such increases would reasonably be expected to be similar to those for offshore turbines i.e. less than 1%, but it is noted that this can be achieved with relatively low technical risk.

11.1.4 Novel technologies

Novel wind generation technologies, such as kites or multi-rotor machines, are in early-stage development and therefore any prototypes and testing would be expected to be performed at an onshore location even if the final product is intended for offshore deployment. If these technologies achieve commercial readiness, they would also be expected to be suitable for onshore installation.

Multi-rotor turbine designs may offer additional advantages to onshore projects, as the smaller individual rotors would theoretically be simpler to transport and could mitigate some of the transportation challenges. Similarly, kite power systems are likely to comprise smaller individual components, and therefore also be easier to move by road.

Airborne genenration technologies, such as kites or tethered airborne turbines, purport to access higher wind speeds at greater altitidues than conventional turbines can reach. Airspace over land is typically more heavily utilised and regulated than that over sea, and therefore onshore installations of such technologies may be limited in altitude, which would also therefore affect power generation and in turn Load Factor.

However, these novel technologies are not expected to achieve commercial viability on utility-scale offshore projects by 2035, and it is unlikely that placement onshore would offer sufficient benefit to accelerate this timescale. Accordingly, it is considered unlikely that these technologies will be deployed commercially in the timeframe of this study. The use of particularly novel technologies is primarily a matter of risk, particular in scenarios where conventional technology is also applicable. It is possible that these technologies may be suitable for remote locations, for example, rather than for established energy markets such as the UK.

11.1.5 Asian turbine OEMs

As the global offshore wind industry expands, new entrants are expected in the turbine market including those from lower-cost jurisdictions. These machines are expected to offer CapEx reductions, which could lead to lower cost of energy.

The onshore wind industry is established in a greater number of geographic locations than is offshore wind, and hence onshore turbines have achieved much wider development and deployment – the onshore wind market in China, for example, is comparable to that of Europe and features a number of domestic turbine suppliers producing proven machines. However, to date, onshore wind turbines from Asian manufacturers have achieved limited penetration into the European onshore wind market.

Whilst lower CapEx is appealing to wind developers, there is a perception that turbines from Asian OEMs may be less reliable during operation, and therefore that OpEx may be increased and availability reduced in comparison with European machines. Therefore, Asian OEMs will need to prove reliability, or guard against potential downsides via contractual protections, to gain confidence from the finance community and achieve commercial success through the mitigation of risk.

There is an increasing focus on the use of "local content" in both onshore and offshore wind farms; turbine supply contributes a significant proportion of project expenditure, and therefore the use of "non-local" turbines would potentially reduce the total local content to an unacceptable level.

Asian turbine OEMs have proven to be very competitive in domestic markets, but less so globally. This may change if the perceived challenges can be mitigated, at which point similar availability would be achieved, and similar technology be deployed, to that of European turbine OEMs and hence Load Factor would also be expected to be similar.

11.1.6 O&M technologies

Recent offshore wind projects have improved O&M practices in efforts to maximise availability and minimise costs; a similar approach applies to onshore wind, albeit through the use of different technologies.

Much of the future offshore wind O&M technology described above is offshore-specific, as metocean conditions are the dominant factor affecting O&M offshore and hence particular attention is paid to enabling work in more onerous conditions via more capable vessels and access systems – these are not necessary for, and therefore not applicable to, onshore wind farms. Personnel access to turbines is considerably simpler for onshore wind farms, although it is noted that onshore projects are commonly situated in remote or challenging locations where access to site can also be limited by weather, and therefore technological advances in onshore wind O&M is more focused on increasing availability through reduction in turbine downtime.

Condition monitoring systems and predictive analytics ("big data") are increasingly being used on offshore turbines to enable the monitoring of machine performance and for scheduled maintenance to be employed to reduce more-costly unscheduled maintenance. These systems are expected to become more widely used as well as more effective, and hence contribute to increased turbine uptime and therefore slightly increased Load Factor, and similar advances are expected for onshore wind. Due to the reduced downtime in the event of failure onshore, the increased availability and hence increased Load Factor is expected to be minimal.

11.1.7 Wind farm control and layout design

Whilst the differences in terrain and scale between onshore and offshore wind farms mean that layout design and control strategies may differ in key parameters, it is expected that these technologies will offer benefits to onshore wind farms as well as those offshore. These technologies are as applicable onshore as offshore, and are expected to gain traction in both industries.

Onshore wind farms often feature complex terrain, and layouts which may be constrained by physical features such as topography, forestry, noise and visual impact. Accordingly, non-regular layouts are common onshore, and hence there may be less scope for varying turbine positions to optimise array efficiency, but it is still likely that some additional benefit could be obtained through reduced wake losses. Layout design approaches and tools have developed as the wind industry has grown, and hence subsequent improvements may be relatively slight without significant changes in methodology; however it is expected that advanced layout design will enable onshore wind farms to exhibit increased energy production, and in turn Load Factor.

Some current wind turbines incorporate control system functions that enable temporary over-production, typically through increased rotor rotational speed, under certain operating conditions (see Section 5.3.2.5). This is most valuable at high-wind sites, where energy production may be increased by up to 2% with a similar impact on Load Factor. The use of such features is expected to continue, noting that the impact on Load Factor is site-dependent and likely to yield a smaller increase for onshore wind farms than those offshore, due to the lower wind speeds.

The complex physical characteristics of onshore wind farms may also mean that advanced control offers operational advantages, through both reduced turbines loads and increased energy production. Advanced control may allow the whole wind farm to generate more power than the aggregate of turbines operating individually, through the control of wakes contributing to increased array efficiency. This would manifest as increased energy production, and hence increased Load Factor. Depending on site conditions and project design, the increase in energy production could be minimal, or up to approximately 2-3%, leading to similar increases in Load Factor. This is also expected to be supported by the use of “big data”, to refine the control systems, for example in wind farm control under particular weather conditions, but which is also expected to be deployed to increase technical availability through improved maintenance scheduling and reduced downtime; this in turn would result in increased Load Factor, although impacts on LF of the latter factors is expected to be minimal.

Advanced control may also enable cost reduction, via the reduction of service loads through wake steering; this may be more effective onshore where turbulence is higher than offshore. Load Factor would not be affected, but both CapEx and OpEx could potentially be reduced by such a strategy, contributing to a lower overall cost of energy from future onshore wind farms.

11.1.8 Electrical transmission system

As offshore wind increases in scale, with larger turbines, larger wind farms and increased distance from shore, the electrical collection and transmission system is also evolving, featuring higher voltages, smaller platforms and dynamic rating to reduce project CapEx and increase efficiency. Much of this is due to the distance from the grid connection point, or the increased costs and complexities of offshore work such as cable installation, and hence there is relatively limited scope for the transfer of technology to the onshore wind industry, where locational and logistical challenges differ.

It is expected that onshore wind electrical infrastructure will continue to evolve, taking into account industry challenges such as remote locations; this is likely to result in technology which is designed for ease of transportation and installation, and for low maintenance – this mirrors the approach taken by the Siemens OTM offshore substation concept, albeit indirectly. Such concepts would contribute to reduced cost of energy and increased Load Factor (through reduced downtime and hence increased availability), albeit slightly.

The further development of offshore grid infrastructure, potentially to include increased interconnection between projects and territories, is unlikely to apply to the onshore industry in the UK, except perhaps in the case of island wind in an effort to share infrastructure costs. Similarly, advanced transmission technologies such as HVDC are unlikely to become common due to the geographic proximity of the transmission grid to the majority of onshore wind projects; again, island wind may be the exception, although any transmission link is likely to be used to connect grids rather than individual projects.

Local storage is expected to be invested in by onshore wind farm owners, which would be used to provide ancillary services to the grid via the wind farm's grid connection; the smaller size of projects and lower Load Factor, relative to offshore wind, may make deployment of storage more feasible for onshore wind. The optimum size and technology of the storage systems would be site-specific, dependent on grid connection capacity and geographical location. It is understood that developers are already investigating the potential for co-locating storage systems at onshore wind farms, and hence commercial deployment is expected in the near future. Storage systems may also enable electricity generated by the wind farm to be sold at times of higher prices, maximising the value of the generated energy. The use of these strategies would be expected to reduce the cost of energy, whilst the storing of generated energy as part of an arbitrage strategy would reduce the overall Load Factor of the project due to the electrical losses of storage systems, by a factor approximately equal to the round-trip efficiency of the selected storage system. Due to the current OFTO regime in the offshore wind industry, it is expected that local storage will be applied onshore more rapidly than to the offshore industry.

11.2 Onshore wind future technologies

Whilst the technologies considered above are primarily related to offshore wind farms, and may also transfer to the onshore wind industry, the following section describes the general technology trends expected to be evident in the onshore wind industry in the period from today to 2035. Overall, it is expected that technology evolution will result in continuation of the historical trends of decreasing cost of energy and increasing Load Factor in onshore wind markets.

Onshore wind turbines are expected to increase in scale, from today's 3-4MW machines into the 5-6MW range. This will necessitate an associated increase in rotor size, with rotors exceeding 150m in diameter having recently been announced by onshore wind turbine manufacturers. The planning constraints and logistical challenges of transporting very large blades by road may mean that segmented blades become common, enabling much longer blades to be delivered to sites than for single-piece designs. However, it is noted that size restrictions also apply to the maximum chord length (cross section) of the blade, for onshore transportation, and this is expected to be mitigated through the development of lighter blades with increased use of carbon fibre composites; this is another technological development expected in both onshore and offshore, although is likely to be proven in the offshore industry before transferring to onshore, due to the variation in turbine size and corresponding structural requirements, and would contribute to reduced cost and increased energy production. Such blades are also expected to become more efficient, for example through the use of aerodynamic devices, which would further increase energy production and Load Factor, recognising that there are diminishing returns to be achieved in this area.

The significant development of the onshore wind industry in the UK, and in other established markets, means that many of the sites with good resource have already been developed; this results in lower-wind sites being available for future development. Accordingly, turbine OEMs have developed specific turbine variants for low-wind deployment, typically with larger rotors relative to the generator capacity. Use of these turbines will open up previously uneconomic sites for project development, but due to the lower wind resource will likely exhibit reduced Load Factors relative to the better sites, even with the low-wind turbines.

Taller towers are also expected to be deployed in efforts to reach higher wind speeds, and thus increase energy production. Towers manufactured from steel and concrete, and hybrid towers combining the two materials, have been developed to date; project preference may depend on factors such as local supply chains. The deployment of taller towers will be dependent on the planning constraints applied to onshore wind. Other technologies used to achieve taller towers include segmented bottom tower sections, which enable a greater lower tower diameter, whilst keeping the individual segments transportable. Also, cable stay towers may be developed as a means to achieve sufficient eigenfrequency of the tower whilst still allowing the tower to be both slender and with a diameter within transportation limits. For wind farms with less restrictive transportation limits, large-diameter towers will be utilized, with base diameters above 6m, to enable tower heights to be increased. Taller turbines may feature in UK projects where visual impact is less of a challenge, for which increased Load Factor would be expected.

With the increase in hub height, requirements to keep the maximum lifting mass within reasonable limits, preferably below 100 tonnes, will lead to increased usage of segmented nacelles and drive trains i.e. nacelle installation will take place in more than one lift. This will enable turbines to increase in size, albeit with increased complexity of installation operations and therefore increased installation cost.

Onshore turbines are expected to continue to increase in availability, through reduced unscheduled maintenance and downtime; this would be achieved through the use of "big data", predictive maintenance and condition monitoring, and increased design-for-maintenance during product development. These approaches will reduce both turbine outages and the length of downtime when failures occur, with fewer technician attendances required and increased generating time; in turn, operating costs will be reduced and Load Factor increased. However, due to the availability of onshore turbines and reduced time-to-repair relative to offshore wind, the expected increase in Load Factor will be less than 1%.

In a competitive environment, such as zero subsidy or support mechanism auctions, financing cost is also significant and hence lower-risk technical solutions may be preferred over unproven new technologies. As a result, and similarly to the offshore wind market, developments of current proven technology are expected to dominate, and novel or disruptive technologies are not expected to make significant advances compared to three-bladed, horizontal-axis turbines that have come to dominate the onshore wind market in the UK and globally.

12 CONCLUSIONS

Offshore wind has been one of the most significant industrial success stories of the early 21st century, achieving rapid deployment and cost reduction to become a mature asset class and contribute a significant proportion of the UK's electrical energy supply. This success is expected to continue, driven by a combination of new and proven technologies and practices, with overall offshore wind Load Factors expected to increase and costs to decrease.

Load Factors of future offshore wind farms are expected to increase in the period to 2035, resulting from the deployment of the next generation of larger offshore wind turbines, together with more advanced wind farm design and control. The magnitude of each individual improvement is relatively small, in low single-digit percentage points, although the aggregate impact will be more significant; these improvements are expected in the next generation of wind farms, which will enter operation in the mid-2020s. These technologies will also contribute to the continuing reduction in the cost of energy from offshore wind, which has seen significant reductions in recent years.

Load Factor is also expected to show a positive trend via increases in turbine and project availability arising from improved operations and maintenance performance, driven by improved accessibility to turbines for technicians to undertake both scheduled and unscheduled maintenance. Existing offshore wind farms are already starting to revise O&M strategies to take advantage of new technology, and future projects are expected to learn from these improvements to achieve higher availability from entry into service. Improvements in availability are estimated to add up to two percentage points to Load Factor.

There are also a number of more radical technologies proposed for offshore wind, that are in earlier stages of technological and commercial development; these include two-bladed turbines, alternative turbine technologies such as vertical axis turbines, and floating foundations. These are not expected to gain a significant foothold in the UK offshore wind market in the timeframe of this study, which is to 2035, due to both the extent of technical development required and the inherent competition with incumbent technologies.

The offshore wind industry expects project Load Factors to increase to over 50% (applicable to a project with mean wind speed of 10m/s; specific projects in locations with better wind resource would be expected to exceed this value) in the period to 2035, primarily due to the deployment of larger and more efficient turbines and improved project design and operation. The industry also expects cost of energy to continue to fall in this period, albeit at a lower rate than has occurred to date. Overall, the industry expects that evolution of existing technologies will dominate, over potential disruptive technologies.

General wind industry technologies are also expected to be applied to future projects onshore, contributing to the continuing improvements in reliability, costs and energy production that are expected to occur in both onshore and offshore wind over the forthcoming two decades.

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APPENDIX A

The industry survey comprised the following questions:

- When do you expect the next generation of offshore wind turbines (10MW+ capacity) to be deployed on commercial projects? Could you give a timescale of expected first deployment for wind turbines of different sizes?
- What level of testing will be required before commercial deployment? Are larger WTGs considered an additional project risk?
- Do you expect that the Load Factor of projects using 10MW+ WTGs will increase versus current projects? By how much will Load Factor increase with turbine size?
- Do you expect the size of offshore wind turbines to plateau within the specified period? At what turbine size?
- In your opinion, what potential does the technology have to reduce overall project costs and in which areas do you see cost reduction? What cost reduction do you think could be achieved?
- Do you expect two-bladed turbines to achieve commercial availability by 2035? If so, when do you expect two-bladed turbines to predominate over three-bladed designs in new projects?
- What impact on Load Factor do you expect for two-bladed turbines versus traditional three-bladed offshore turbines?
- Do you expect significant developments in blade design, that will unlock increased turbine performance and Load Factor? How much do you expect that these will reduce LCOE and/or increase Load Factor?
- What innovative rotor technology do you expect to be developed on 100m+ blades on future offshore turbines? Do you expect the Load Factor of projects using this to increase versus current projects, and by how much?
- Is there any appetite in the industry / your organisation for hardware modifications i.e. blade aerodynamic attachments, during the operational phase of projects? If so, how much is this expected to increase Load Factor and/or reduce operational costs?
- When do you think airborne turbines or multi-rotor concepts will become commercially available and competitive with conventional turbine technology?
- When do you expect offshore wind turbines from Asian OEMs to be deployed globally?
- What potential does the technology have to reduce overall project costs and in which areas do you see cost reduction? How much cost reduction do you think could be achieved?
- Do you expect the next generation of SOVs and walk-to-work systems to significantly increase the WTG availability and Load Factor of offshore wind farms? By how much?
- What technology improvements will need to be achieved in helicopter access to significantly increase the availability of projects? Do you expect that helicopter access will become more common than SOVs? How much can helicopter access decrease the costs and increase the Load Factor of projects?
- Do you expect the next generation of crew transfer vessels with increased sea and speed capabilities to significantly increase the LF of future projects? If so when do you expect this to be deployed on commercial projects? How much will the LF increase by?

- When do you expect floating offshore wind turbines to be deployed on commercial projects? In which markets do you first expect to see large scale commercial deployment? What do you consider as the main barriers for commercial offshore floating wind deployment, if any?
- How do you expect the Load Factor and performance of floating offshore wind farms to compare to that of bottom-fixed projects?
- What do you see as the main advantages of floating wind turbines compared to bottom-fixed offshore wind turbines?
- What potential does the technology have to reduce overall project costs and in which areas do you see cost reduction?
- Do you expect advanced wind farm control strategies and systems (i.e. wake steering) to become the default control approach?
- If so, what do you see as the primary benefits? How much can these systems increase Load Factor or reduce costs over current windfarms?
- Do you expect that advanced layout design will be able to offer performance benefits to future projects? If so, what needs to happen to enable project optimisation to be utilised? How much could layout optimisation increase energy production?
- Do you expect HVDC to be commercially viable on individual offshore wind projects? And what impact do you expect on load factor from the use of HVDC?
- Do you expect any advances in power transmission technology, that would improve system efficiency and Load Factor, by 2035? By how much would it increase system efficiency and Load Factor?

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